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FINAL TECHNICAL REPORT

AFFDL-TR-69-24

DEVELOPMENT OF A MINIATURE CAPACITIVE RESOLVER

by

Donald W. Howarth
and
Robert A Kawcyn

April 1969

Prepared for

Air Force Flight Dynamics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Under

Contract No. F33615-68-C-1181

Prepared by

Litton Systems, Incorporated
Guidance and Control Systems Division
5500 Canoga Avenue, Woodland Hills, California 91364

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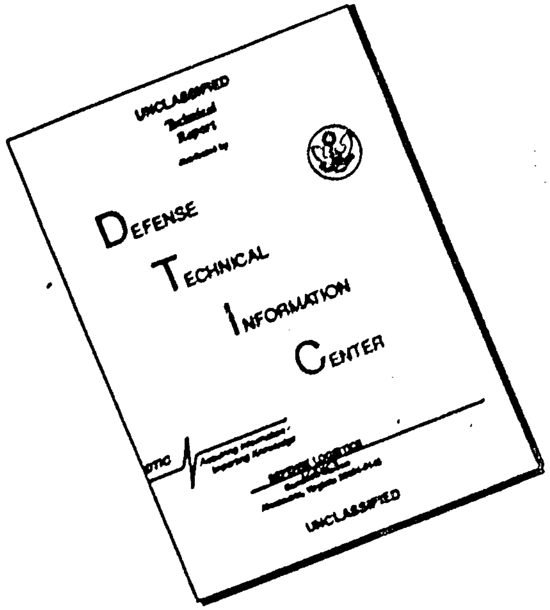

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FOREWORD

This final technical report entitled "Development of a Miniature Capacitive Resolver" was accomplished by the Advanced Development Projects Section of the Applied Research Directorate of the Guidance and Control Systems Division, Litton Systems, Inc., Woodland Hills, California, under Air Force Contract F33615-68-C-1181, Project No. 8222, Task No. 822203. The Litton project manager was Mr. Donald W. Howarth and the work was administered by the Air Force Flight-Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Dr. Anthony DeThomas of the Control Elements Branch was the project engineer.

The authors wish to acknowledge the participation of Mr. John G. Mark in much of the analysis and programming, of Mr. Harry Newhoff for his early contributions as principal engineer, and of Mrs. Avis McCarthy for her invaluable assistance in data collection and reduction and software debugging.

This work describes the work accomplished during the period January 1968 to April 1969. This report was submitted by the authors in April 1969 for publication as a technical report.

This technical report has been reviewed and is approved.

H. W. Basham
Chief, Control Elements Branch
Flight Control Division
AF Flight Dynamics Laboratory

ABSTRACT

A miniature, pancake-style resolver which employs the principle of measuring the capacitance between a plane parallel electrode structure has been developed. One-half contains a pattern structure electrically excited by 100-Khz voltage; the other consists of a pickoff structure whose output signals are proportional to sine and cosine functions of the angular displacement of the two elements. This entire assembly, and its signal processing electronics, is 0.9 inches in diameter and 0.13 inches thick. Its accuracy is at least 10 arc-minutes. Theoretical discussion includes pattern and pickoff element design, mechanical and electrical error analysis, and electronic design. Experimental discussion includes the computer-generation of patterns and pickoff geometries, the fabrication of the elements using the thin-film techniques of the semiconductor industry, and construction of an electronics package using hybrid microcircuits. A special mechanical test fixture which allowed the deliberate introduction of positional errors to evaluate their effects on accuracy was developed. Preliminary work on a 1.5-inch diameter model is also given.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Definition
A	Area of a pattern function, or portion thereof
A	Amplifier gain
Å	Angstrom units, 1 Å = 10^{-8} centimeters
a, b	Coupling coefficients from capacitive resolver pickup plates
A mode	Excitation of all pattern elements from same voltage
B mode	Excitation of pattern from balanced voltage source
C	Capacitance
d, e, f	Axis displacements in eccentricity error discussions
e	Generalized ac signal voltage; e_i for input voltages; e_o for output voltages
E	Generalized voltage
FET	Field effect transistor
g	Gap between plates of capacitive resolver
g_o	Mean, or "standard" gap
G	Generalized gain
h	Half of clearance from outer edge of disc metallization to outer edge of substrate
j	Complex operator
k	Coefficient in error expression $k = \frac{a}{b}$
K	10^3 (used when referring to component magnitudes)
k	Generalized constant
ma	Milliamperes
mv	Millivolts
pf	Picofarads (10^{-12} farads)

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LIST OF SYMBOLS AND ABBREVIATIONS (cont)

Symbol	Definition
r	Generalized radius, independent variable
R	A mean radius of a circular pattern
R	Resistance
r_o, r_i	Outer and inner radii in circular patterns
R_o, R_i	Outer and inner radii of substrates
s	Laplace transform operator
TIR	Total indicated runout
W	A width in a pattern generating function
Z	Impedance
Z_f	Feedback impedance in operational amplifier configuration
Z_i	Input impedance in operational amplifier configuration
α	Angle of tilt of pattern surface from normal to its axis of rotation
α	Is proportional to
$\bar{\alpha}$	Pattern relative tilt $\bar{\alpha} = \alpha \frac{R}{g_o}$
α, β	Variables in eccentricity discussion $-\alpha = +\frac{e}{R}\cos\theta - \frac{f}{R}$ $-\beta = \frac{e}{R}\sin\theta$
β	Angle of tilt of pickoff from normal to its axis of rotation
β	Feedback ratio
$\bar{\beta}$	Pickoff relative tilt $\bar{\beta} = \beta \frac{R}{g_o}$
ϵ	Normalized width in a three-element pattern $= \frac{W}{2R}$
ϵ'	Normalized width in a 2-element circular pattern $= \frac{W}{R}$
θ	Angular variable in pickoff geometry discussions

LIST OF SYMBOLS AND ABBREVIATIONS (cont)

Symbol	Definition
θ_e	Angular error of capacitive resolver
θ_o	Direction angle in eccentricity error discussions
μ	Direction of pattern tilt from zero of pattern generating function
ρ	A radius vector in eccentricity error discussions
σ	Standard deviation
σ	Direction of pickoff tilt from center of cosine plates
ϕ	Angular variable in pattern function discussions
ϕ	Phase shift
ϕ_o	Direction angle for ρ in eccentricity error discussions
ω	Angular frequency in radians per second (may be scaled by a power of 10)

SECTION I

INTRODUCTION

1.1 PURPOSE

A continued pressure toward smaller, more sophisticated airborne systems has identified a requirement to develop smaller sensors that will be needed to implement these systems. A study of miniaturized inertial navigation systems pointed to the lack of a platform angle sensor that would satisfy the extreme requirements of small size and potential low cost and be compatible with the inertial sensors and other components which are in close proximity in a miniaturized configuration.

1.2 RESOLUTION

To meet these needs, the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, placed a contract with the Guidance and Control Systems Division of Litton Systems, Inc., for the investigation of a miniature capacitive resolver. The requirements for the capacitive resolver grew out of a proposal that Litton made to FDL and evolved from work done in a developmental program in 1963-4. This earlier work with capacitive angle sensors identified problem areas in the design and fabrication of a resolver-like element which has signal processing electronics as an integral part. Surprisingly, these problems are resolved, for the most part, when the device is made smaller. The capacitive resolver configuration chosen as a basis for the present work is a pancake-like structure, with the capacitor electrodes (or plates) resembling two opposed annuli. The accuracy of the device is dominated by the quality of the two electrode surfaces, and by the uniformity of the space between them. As the sizes of the elements of the capacitive resolver approach the size of silicon semiconductor wafers, the highly sophisticated materials and processes of the whole semiconductor technology become available for the precise fabrication of these elements. Furthermore, the entire fabrication process is compatible with the design requirements for having the signal processing electronics as an integral part of the device, and at potentially low cost.

1.3 CONTRACT REQUIREMENTS

Work was started on 8 January 1968 on Air Force Contract Number F33615-68-C-1181, for the development of a miniature capacitive resolver and was concluded 1 April 1969. The contract requirements were to design and develop the processes required to fabricate a device 0.9 inches in diameter and 0.13 inches high whose electrical output would be proportional to the sine and cosine functions of the angle through which the device was rotated, to a design goal accuracy of 10 arc minutes of angle (not to exceed 30 arc minutes of angle), and to evaluate the principal error contributors to this device.

SECTION II

GENERAL DESIGN CONSIDERATIONS

2.1 SCOPE

This section discusses the various mechanical and electrical design considerations and trade-offs required in a miniature capacitive resolver.

2.2 CONFIGURATION

The requirements imposed on a capacitive resolver by its installation in and around the bearing journals of the gimbals of a miniaturized inertial platform restrict the size and shape of the device severely. In general, the signal-to-noise ratio and the resulting precision of the device increase with an increased signal output level, and since the signal transferred through a capacitance is proportional to the capacitance, it is desired to have as large a capacitance as is consistent with other packaging constraints. Closely spaced opposed discs accomplish this, and this geometry allows for precise fabrication. The coupled signal in a capacitive device, formed from two opposed discs, is proportional to the square of its diameter and is inversely proportional to the gap separating the discs. With length (or height) and diameter at a premium, the design trend is to the smallest practical gap. Another constraint that further defines the shape of the device arises from the practical problem that is associated with the gimbal bearings. Any bearing system that would surround or enclose the device would naturally increase its diameter, and thus conflict with miniaturization requirements. In addition, since the incremental area between opposing plates at any radius increases as the radius, the outer margins of a capacitive resolver should be used for the capacitance area and the inner areas used for bearings and shafts. Thus the disc becomes an annulus, with a hole through its center large enough for a stiff shaft to extend through it.

The form of the miniature capacitive resolver is restricted to a set of thin opposed washer-like elements. The size is defined as a design requirement of the program: 0.9 inches in diameter, with a 0.37-inch diameter hole in its center, and with a total height, including signal processing electronics, of 0.13 inches. An outline drawing is shown in figure 1.

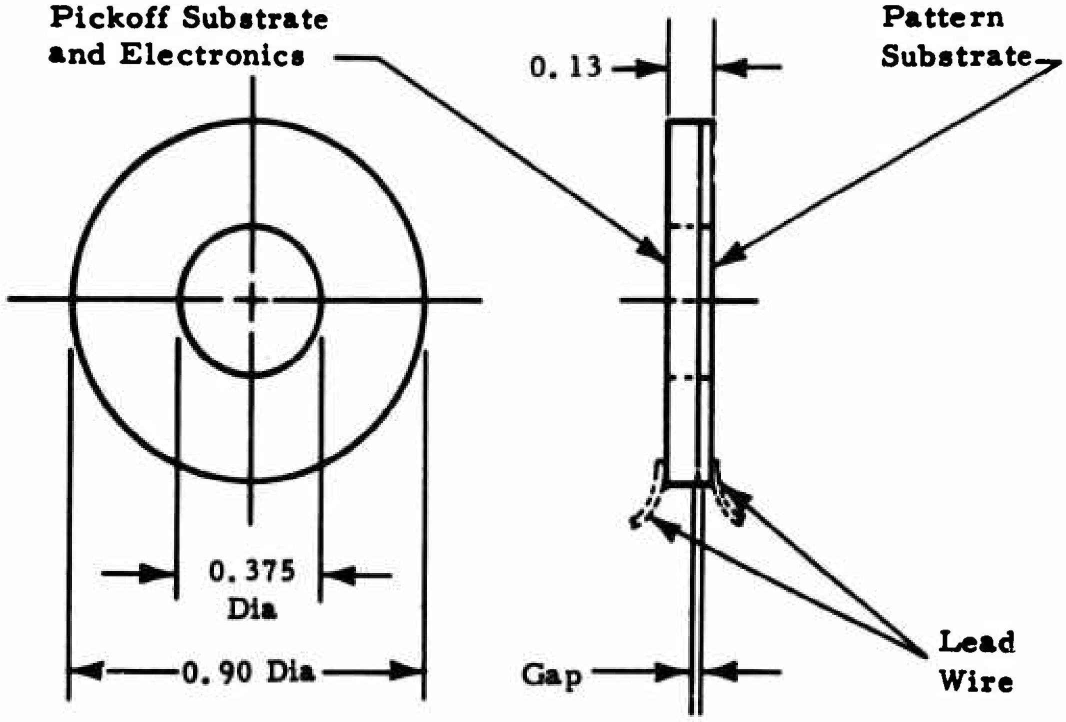


Figure 1. Outline Drawing of Complete Capacitive Resolver Package

2.3 ELECTRICAL PERFORMANCE REQUIREMENTS

Consideration of the electronics requirements for the capacitive resolver shows that it is primarily a problem in impedance matching. The classical electromechanical servo elements are inductive devices, operated at low audio frequencies, and characterized by impedance levels of a few hundred to a few thousand ohms. Here, however, concern is with passing usable electrical signals through quite small capacitances, typically 10 picofarads or less The reactance of such a capacitance at low audio frequencies, e.g., 1 kilohertz, is enormous (16 megohms for 10 pf); thus, high operating frequencies are employed to reduce the impedance to a reasonable level. Current planning for future guidance systems involves frequencies of 100 Khz, and this value will be employed here. At 100 Khz, one can employ rather conventional signal processing techniques with RC type components; frequencies much higher than this will usually require resonant circuits, using inductors in addition to resistors and capacitors, and should be avoided because of the difficulties inherent in miniaturizing inductive components. It will be shown that commercial integrated operational amplifiers are of great use in this application, and the upper limit of their performance is being approached at 100 Khz.

The general design of the capacitive resolver should not result in a system which requires complicated electronic signal processing, either in the area of supplying voltages to the driven elements or in processing the signals from the pickoff elements. This is especially true for the pickoff electronics, since it is desired to keep in mind the possible goal of preparing the pickoff electronics as a single, low-cost, monolithic circuit.

2.4 MATERIALS AND PROCESSES

The materials and processes that are used in fabricating elements of the miniature capacitive resolver have been chosen with an eye toward the eventual production cost of this device. The utilization of semiconductor related processing techniques implements fabrication and assembly methods of potentially low cost, provided that the choice of materials and the detail shape of various elements do not eliminate that potential. In general, the capacitive resolver is not limited by fabrication techniques because it is orders of magnitude larger than the typical semiconductor devices that are made with similar metallization and interconnection processes. A smaller resolver would be potentially no more costly to fabricate than one 0.9 inches in diameter, however, its performance might suffer somewhat from signal-to-noise problems.

During the course of the program, methods and material systems were used that are compatible with the philosophy of potential low cost, and are not limited to a device of exactly the size specified. While fused quartz was used as a substrate material in the developmental steps, an end item substrate material is probably alumina or a similar dimensionally-stable ceramic. The signal processing electronics were built in an unsophisticated hybrid microelectronic assembly for the engineering model, being a combination of discrete components, thin film networks, integrated circuit amplifiers, in chip form, and epoxy/glass-etched circuitry. The electronics eventually will become part of the pattern or pickoff substrate fabrication with a very minimum of discrete components as more large scale integrated circuitry becomes available. Again, the potential low cost end item is a goal.

2.5 PROGRAM TASKS

The program to develop a miniature capacitive resolver is broken into a series of development tasks that fall into three groups.

The first group consists of those tasks that are associated with the design, fabrication, test, and evaluation of standard pattern and pickoff configurations for the capacitive electrodes. The usage here is that the pattern electrode is the insulated disc having on its surface a metallic pattern driven by an external voltage source; the pickoff is a similar disc whose metallic layout, in close proximity to the pattern disc, picks up the

signals capacitively coupled from it and delivers them to the signal processing electronics. The second group of tasks centers on the design, fabrication, test, and evaluation of the signal processing electronics that will be an integral part of the device. The third group is comprised of a single task; the design, fabrication, test, and evaluation of an engineering model of the 0.9-inch diameter capacitive resolver.

SECTION III

CAPACITIVE PATTERN AND PICKOFF DESIGN

3.1 SCOPE

The various possible geometries available for annular patterns are discussed here; an appropriate choice minimizes certain errors and simplifies the signal processing. Pattern generation with a computer-controlled plotter is described, together with artwork and scaling problems.

3.2 PATTERN SELECTION

The desired output of the capacitive resolver is a signal that is proportional to the angle through which the device is rotated, and is continuous, so that no discontinuities or ambiguities are encountered regardless of the initial starting point, the direction of rotation, and the magnitude. These constraints are all satisfied by the periodic sinusoidal functions, sine and cosine, and these, of course, are the output functions of the classic electromagnetic resolver.

First consider a simplified problem using rectangular coordinates. The simplest of patterns for this geometry is shown in figure 2, where the independent variable is, for future convenience, called θ. There is a metallic surface of total width $2W$ and indefinite length, divided into two parts or elements by an infinitesmally thin boundary generated by the function $W\cos\theta$. The upper half of this pattern, shown cross-hatched, is excited by an a-c voltage source and the other, unshaded half, by a similar voltage source of exactly equal amplitude and opposite phase.

The metal pickup areas are shown as the dotted rectangles of height $2W$ and width $2\Delta\theta$, and are positioned identically above the pattern plane. They are constrained to motion only in the θ direction. The geometry here is that of the classical plane parallel plate capacitor, and all fringing effects are to be neglected. The capacitance between the pickoff and pattern areas is thus directly proportional to the common surface area between them, and a signal on a pickoff plate may be spoken of as being equal to an area, with the capacitive coupling coefficient assumed.

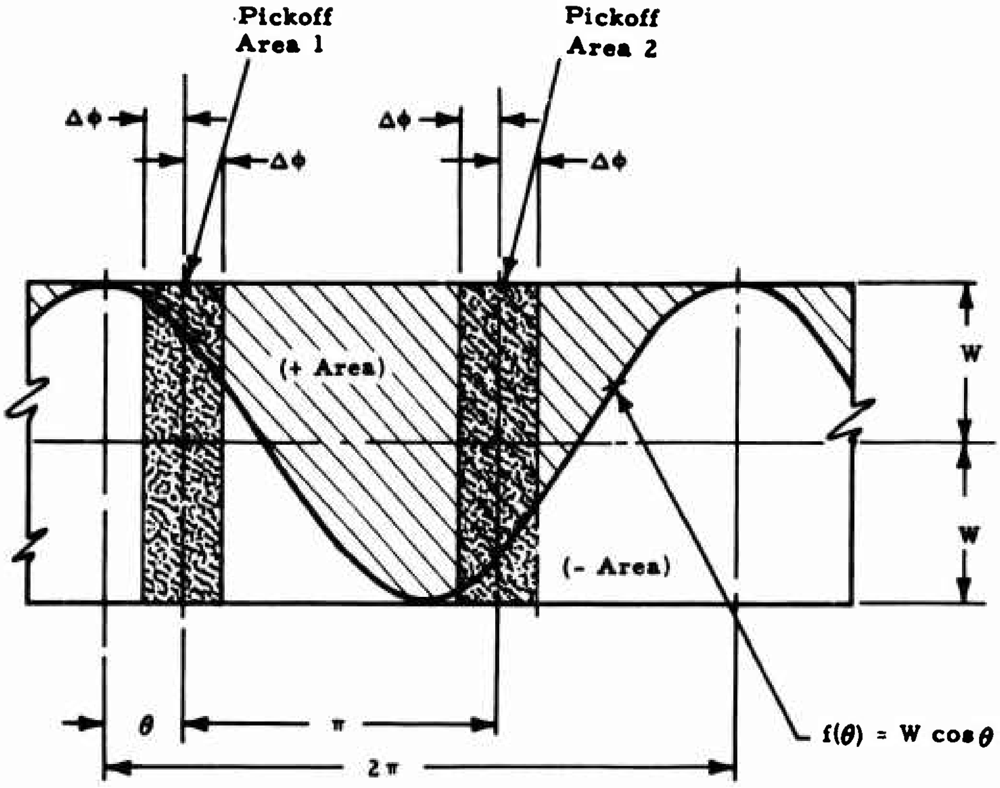


Figure 2. Simple Sinusoidal Pattern in Rectangular Coordinates

Note also that the use of voltages of equal magnitude and opposite phase on the pattern elements allows the use of the principle of superposition to obtain the net effect on a pickoff element of the two coupled areas: It may be said that a positive voltage, or area, "induces" a positive signal on the pickoff; similarly a negative signal results from the area with a negative voltage and, since the magnitudes of the pattern voltages are equal, the net effect is simply the difference in coupled areas. Therefore, the net coupled signal is calculated simply from:

$$A(\theta)_{net} = \int_{\theta-\Delta\phi}^{\theta+\Delta\phi} \left[A(\theta)_{positive} - A(\theta)_{negative} \right] d\theta \qquad (3.1)$$

where

$A(\theta)_{positive}$ = $W(1-\cos\theta)$, the height of the upper element

$A(\theta)_{negative}$ = $W(1+\cos\theta)$, the height of the lower element

then:

$$A(\theta)_{net} = -2W \int_{\theta-\Delta\phi}^{\theta+\Delta\phi} \cos\theta d\theta = -4W\sin\Delta\phi\cos\theta \qquad (3.2)$$

A second pickoff area (area 2, figure 2) displaced from the first by π will have coupled to it a similar net signal of the same magnitude but opposite in sign, assuming, of course, that the areas are of the same width, and in the case of a capacitor, are coupled with the same gap. A third and fourth set of pickoff areas (not shown in the f gure), each displaced from the first two by $\pi/2$, would have coupled to the the complementary sinusoidal function. The output of the two pairs t ı, would be:

$$E_{12}(\theta) = \alpha\left[A_1(\theta \quad (\theta)\right] = -E\cos\theta$$

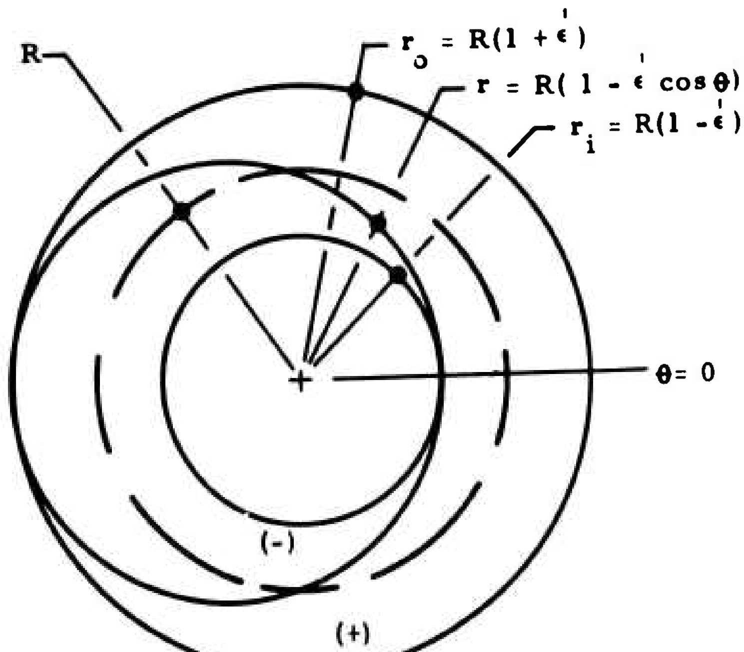
$$E_{34}(\theta) = \alpha\left[A_3(\theta)-A_4(\theta)\right] = +E\sin\theta \qquad (3.3)$$

These output signals would be maximum (in gain) when the four plates filled the space 2π, or were each $\pi/2$ wide. With the foregoing constraints, these output signals are exactly proportional to the complementary sinusoidal functions, and free from error terms. It would appear then that the simple pattern of figure 2 is the ideal pattern for the capacitive resolver, and needs only to be mapped on the desired surface in order to achieve a theoretically error-free output signal. If the surfaces were cylinderical, such would be the case, but when the surfaces are annuli, error terms are introduced.

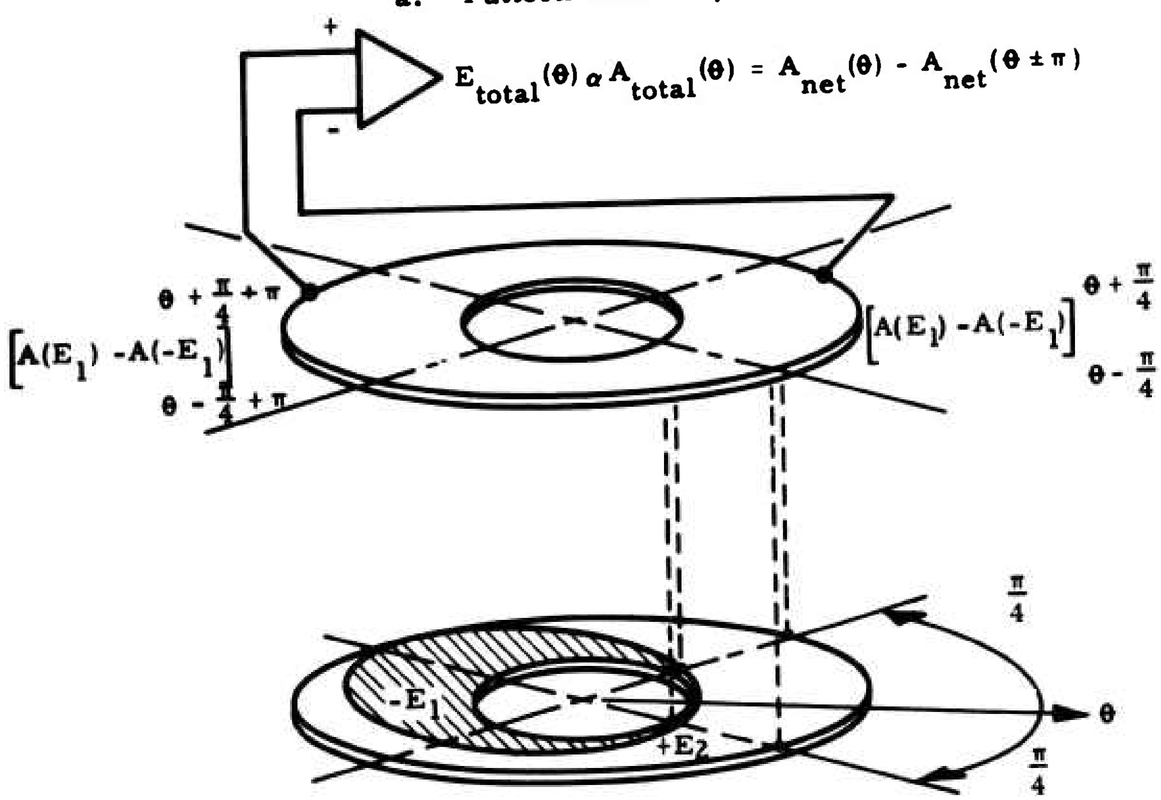
3.3 THE TWO-ELEMENT PATTERN

Consider the pattern shown in figure 3a. This is simply the pattern of figure 2 mapped on an annulus; that is, two pattern elements separated by a line that is generated by the function $R(1-\epsilon'\cos\theta)$, where R is the mean radius of the annulus and ϵ' is its normalized width (W/R). Visualize a matching annular pickoff sector of width $\pi/2$, coupling signal from both the positively and negatively driven pattern elements as shown in figure 3b. This net area coupled from one pickoff plate will be:

$$A_{net}(\theta) = \int_{\theta-\pi/4}^{\theta+\pi/4} \left[\int_{r}^{r_o} \rho d\rho - \int_{r_i}^{r} \rho d\rho\right] d\theta \qquad (3.4)$$



a. Pattern Geometry



b. View with Circular Pickoff

Figure 3. The Two-Element Circular Pattern

$$A_{net}(\theta) = 1/2 \int_{\theta-\pi/4}^{\theta+\pi/4} \left(r_o^2 - 2r^2 + r_i^2 \right) d\theta \qquad (3.5)$$

$$A_{net}(\theta) = R^2 \epsilon' \int_{\theta-\pi/4}^{\theta+\pi/4} \left(2\cos\theta + \epsilon' \sin^2\theta \right) d\theta \quad . \qquad (3.6)$$

$$A_{net}(\theta) = 2R^2 \epsilon' \sqrt{2} \left[\cos\theta + \frac{\epsilon' \sqrt{2}}{8} \left(\frac{\pi}{2} - \cos 2\theta \right) \right] \qquad (3.7)$$

The output of a single pickoff quadrant contains not only the desired single speed term, $\cos\theta$, but also zero and second speed terms, which here contribute unwanted components, or errors. When opposite pickoff quandrants are subtracted, however, the errors cancel:

$$\begin{aligned} A_{total}(\theta) = A_{net}(\theta) - A_{net}(\theta \pm \pi) &= 4R^2 \epsilon' \sqrt{2} \cos\theta \\ &= 4RW\sqrt{2} \cos\theta \end{aligned} \qquad (3.8)$$

and the output function is exactly sinusoidal provided, of course, that the addition (or subtraction) is exact. This signal processing is done electronically (with operational amplifiers) in the miniature capacitive resolver, and therefore, will place gain-matching constraints on these electronics. If a pattern whose net coupled signal from each pickoff quandrant is exactly sinusoidal can be found, then the matching constraint on the electronics could be relaxed. The pattern which satisfies these criteria turns out to be a simple extension of the two-element pattern.

3.4 THE THREE-ELEMENT PATTERN

Consider the pattern shown in figure 4, and again visualize an opposed annular set of pickoff quandrants. The generating functions are $r = R[1 \pm \epsilon(1-\cos\theta)]$, where R is, as before, the mean annular radius and ϵ is the normalized annular half-width (W/2R). The net coupled signal to a pickoff quadrant is:

$$A_{net}(\theta) = \int_{\theta-\pi/4}^{\theta+\pi/4} \left[\int_{r_k}^{r_o} \rho\, d\rho - \int_{r_j}^{r_k} \rho\, d\rho + \int_{r_i}^{r_j} \rho\, d\rho \right] d\theta \qquad (3.9)$$

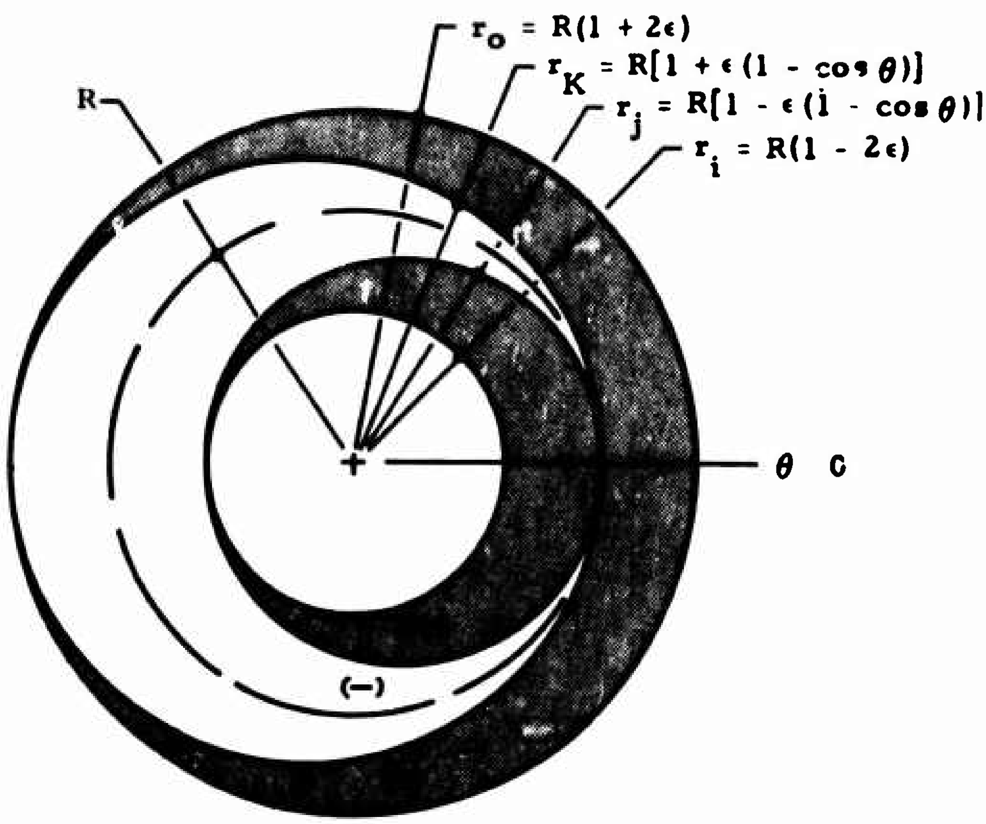


Figure 4. The Three-Element Circular Pattern

$$A_{net}(\theta) = 1/2\int_{\theta-\pi/4}^{\theta+\pi/4}\left[\left(r_o^2 - r_i^2\right) - 2\left(r_k^2 - r_j^2\right)\right] d\theta \tag{3.10}$$

$$A_{net}(\theta) = 4R^2\epsilon\int_{\theta-\pi/4}^{\theta+\pi/4}\cos\theta\, d\theta = 4R^2\epsilon\,\sqrt{2}\cos\theta \tag{3.11}$$

This is exactly the desired output function, without any error terms. In a similar manner to the two-element pattern, the signals from opposite plates may be combined to double the output voltage.

$$A(\theta)_{total} = 8R^2\epsilon\,\sqrt{2}\cos\theta = 4RW\,\sqrt{2}\cos\theta \tag{3.12}$$

Note that the magnitude of the output function $A(\theta)_{total}$ depends only on R, W, and θ, and is independent of the choice of the two-or three-element pattern.

This three-element pattern was chosen as the standard pattern for the miniature capacitive resolver.

3.5 PATTERN GENERATION

The resolution of detail that can be attained in a semiconductor related photo-image-and-etch process places a constraint on the generation of artwork and subsequent reduction to masks if accuracy commensurate with the processing capabilities is to be preserved. While semiconductor artwork is typically made up of elements of straight lines and circles, which are simple to mechanize in artwork, the three-element pattern, while it contains circles and straight lines, is principally the locus of a continuously varying analytic function. Though this pattern can be generated kinematically (in fact, a model of a mechanical pattern generator was fabricated early in the program to evaluate its effectiveness) it soon becomes apparent that, if for no other reason than scaling, a mechanical technique is to be avoided. The mechanical plotting device itself has the serious drawback of cutting or inking too thick a pattern line unless the pattern artwork is many times actual size. Also, the looseness of fit or backlash between the many interrelated moving pieces of the mechanism is intolerable.

Hand plotting and cutting (or taping) artwork of huge dimensions is also a poor approach, particularly when standard pattern artwork is to provide an essentially error-free pattern that will be used to evaluate mechanical perturbations such as tilt and eccentricity.

The ideal pattern generator would plot 10X or 20X artwork, accurately to within 0.001 inch, and the plotting trace of the pattern (and later the pickoff quandrants) would, when reduced, be capable of imaging a continuous etched line of 0.0005 to 0.001-inch width in a thin metal film. Litton's Gerber plotter, a computer controlled coordinatograph of high precision, was applied to this pattern artwork generation. The machine is programmed specifically for the making of highly accurate 1 to 1 artwork for multilayer interconnection laminates. Precise analytic function plotting had not been attempted with the Gerber other than an occasional try at some three-dimensional graphics as output for computer programs.

The Gerber plotter has a plotting area 40 x 40 inches and a plotting head which is driven incrementally from a digital control unit to within 0.0008-inch true position. In one mode of operation, a light pencil mounted in the plotting head images a narrow beam of light on a photo-sensitive surface, which is then processed directly to a negative (or positive) artwork or mask. The plotting routine for the three-element pattern requires that the four generating functions meet at three points in the pattern (or when a finite line is being plotted, overlay exactly at three points). The plotter is driven incrementally in x, y coordinates, so that the program raster and the round-off error accumulation are of importance in a plotting scheme where the end point is four revolutions (or pattern generation) away from the starting point, as shown in figure 5. An input program was written to generate the

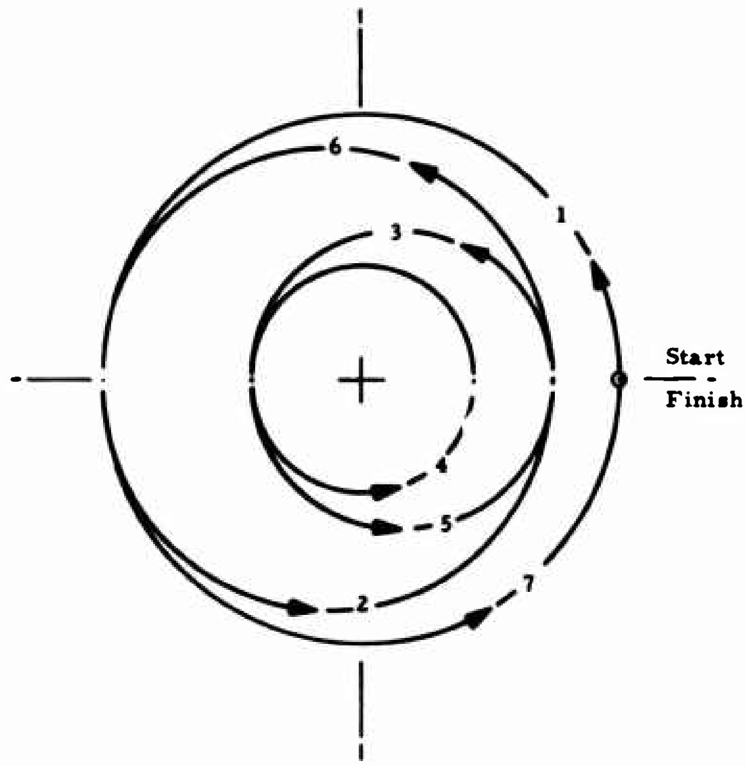


Figure 5. Plotting Sequence for Computer-Generated Artwork of the Three-Element Pattern

incremental x, y inputs to the plotter. This program, in which round-off error accumulation was limited to one part in 10^5, provided that a 10X artwork for the 1.5-inch diameter pattern/pickoff would be plotted accurately to within 0.001 TIR across 18 inches. The input program reduces not only the exact generating function but a general analytic function as well to x, y increments. The program also provides that pattern correction terms, in the form of Fourier coefficients derived from standard pattern testing, could be added back into the generating function (in the correct sense) to reduce pattern error in the next generation of patterns.

3.6 PATTERN SCALING

The pattern generating functions are scaled by two parameters; R, the mean radius, and ϵ, the normalized (half) width of the annulus. Two sets of standard patterns and pickoffs were fabricated, one to match the end item pattern size (slightly less than 0.9-inch diameter) and the other as large as could comfortably be accommodated in the semiconductor wafer related processing equipments (slightly less than 1.5 inches in diameter). The scaling is so arranged that only the mean radius, R, is changed between the two sizes. This was done to provide the maximum amount of test data correlation between the two patterns. These parameters are established for the 0.9-inch diameter configuration, referring to figure 6, one obtains:

$$R = \frac{r_o + r_i}{2} = \frac{(R_o - 2h) + (R_i + h)}{2} = \frac{R_o + R_i - h}{2} \qquad (3.13)$$

where

r_o = outer edge of metallization

r_i = inner edge of metallization

R_o = outer edge of substrate

R_i = inner edge of hole in substrate

$2h$ = clearance from outer edge of metallization to outer edge of substrate

R = pattern mean radius.

For the 0.9-inch O.D. x 0.375-inch I.D. constraints of the engineering model:

R_o = 0.45 in.

R_i = 0.1875 in.

$2h$ = 0.025 in.

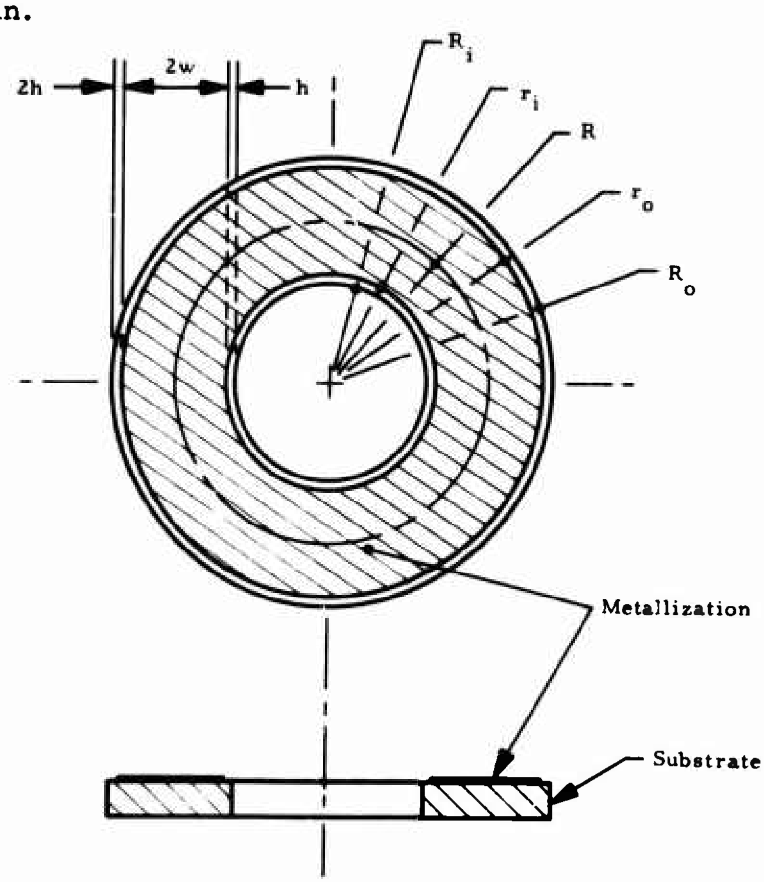


Figure 6. Pattern Scaling Parameters

then,

$$R = \frac{0.45 + 0.1875 - 0.0125}{2} = 0.3125 \text{ inches}$$

The normalized width is defined as

$$\epsilon = \frac{W}{2R} \tag{3.14}$$

where

$$\begin{aligned} 2W &= r_o - r_i = (R_o - 2h) - (R_i + h) = \\ R_o - R_i - 3h &= 0.45 - 0.1875 - 0.0375 = 0.225 \text{ inches} \end{aligned} \tag{3.15}$$

so that

$$\epsilon = \frac{0.225/2}{2(0.3125)} = 0.18$$

The three-element pattern artwork was plotted on stabilized photographic film at 20X, and the light pencil aperature was set at 0.010 inch. The input plotting parameters were:

$$R = 6.25 \text{ inches}$$

$$\epsilon = 0.18 \text{ inch}$$

The resultant artwork was reduced photographically to working masks by a semiconductor mask-making vendor (Electromask, Inc. of Van Nuys, California).

SECTION IV

STANDARD TEST PATTERN AND PICKOFF FABRICATION

4.1 SCOPE

In this section, the choice and fabrication of the substrate material are described, indicating the difficulties with ceramics and plastics, and describing the use of fused quartz, the final choice.

4.2 MATERIAL SYSTEMS FOR STANDARD PATTERNS

The requirements of the standard patterns limit the range of materials and processes that can be used to fabricate them. While it is desirable to work with material systems early in the program that will be candidates for the end-item device, the constraints placed on a "standard of measure" soon restrict the choices to those having the attributes of simplicity, accuracy, and stability.

Two systems of materials that had potential end-item merit were considered initially. The first of these used a magnesium silicate material, Ceramsoft, as a substrate. The pattern metallization was a vacuum deposited thin film of nichrome and gold. The pattern was connected electrically to the opposite side of the substrate through holes that were filled with electroplated copper. The system was chosen because it had a significant advantage over others first considered; the substrate material could be machined in the "green" or unfired state and, when fired, experience negligible dimensional change. This material had, in fact, been employed in certain places in inertial instrument construction where these properties allowed the ceramic-like material to be machined into intricate shapes and then fired. The disadvantages of the system, however, were significant. The fired substrate material was porous and it was difficult to obtain a smooth surface, even by lapping the fired material. This granularity or porosity also made both vacuum deposition and electroplating of metals a processing problem. Because the substrate material was difficult to clean, it behaved like a "sponge" for all sorts of unwanted contaminants. The result was poor quality metallization that resulted in even poorer quality etched patterns, particularly the harsh etch required for gold. The substrate material proved to be very sensitive to mechanical strains, particularly local ones.

The process of electroplating copper into the small holes caused many of the substrates to crack and spall at these locations. A few metallized substrates, 1.5 inches in diameter and 0.15 inches thick, were processed, and the first pattern and pickoff topologies were etched in them. Their surfaces were not flatter than 0.0005 inches TIR across the 1.5 inches, and were not stable. However, two were installed in the test fixture and performance measurements were made. The data contained enough information to point out a problem in the Gertsch resolver turntable. This material system, however, was rejected, particularly for the purpose of making standard patterns.

A second system of materials that was considered, again because of its potential end-item cost, uses a plastic material as a substrate, with molded-in electrical feedthroughs, and a vacuum-deposited metal as the pattern electrode. The substrate surfaces of a number of the filled epoxy materials could be finished to a high quality. However, none of the materials that were evaluated exhibited sufficient stability to allow its use as a standard of measurements. All of them changed by tenths of thousandths of an inch over the period of a week.

4.3 QUARTZ SUBSTRATES FOR STANDARD PATTERNS

Fused quartz was finally chosen as the substrate material for standard pattern work. It is difficult to fabricate, requiring the skills of the optics industry, but it provides an excellent defect-free substrate surface upon which to vacuum deposit a thin metal layer, and can be heated to the temperatures that are required to obtain good adherence of the metal without fear of damaging the substrate. The material is stable and can withstand the stresses of a combination of metallizing processes and subsequent mechanical attachment of electrical connections with no loss of this important quality. Its principal drawbacks are its cost (as a material) and the difficulties in fabricating shapes with it.

The standard pattern substrates are processed as blank discs, 1.5 inches in diameter, and 0.15 inches thick, with a lapped and polished surface flat to within 50 millionths of an inch. Feedthrough holes, 0.020 inches in diameter are drilled through the discs; three in the pattern disc and four in the pickoff disc, prior to the final surface finishing processes. The holes are metallized with palladium, then gold plated, and are subsequently filled with a low-temperature solder which is brought flush to the surface of the substrate.

4.4 VACUUM DEPOSITED ALUMINUM STANDARD PATTERN

A thin aluminum film is vacuum-deposited on the surface of the quartz substrate, and this aluminum is processed subsequently as if it were the metallizing layer on a semiconductor wafer. It is coated with a photoresist, then the pattern (or pickoff) lines are exposed through a mask, in an apparatus used to align semiconductor masks. The resist is developed and the exposed metal is etched, leaving a set of 0.7 to 1.0-mil lines separating the

aluminum pattern or pickoff elements. The process is clean and straightforward and provides a metal pattern of high resolution and durability. Those standard patterns made early in the program are still serviceable, although they have been handled repeatedly for nearly a year.

4.5 1.5-INCH DIAMETER STANDARD PATTERN SET

The 1.5-inch diameter standard pattern and pickoff substrates for the capacitive resolver were fabricated with the process outlined in the preceding paragraphs. The substrate is fused quartz and the capacitive electrode patterns are etched in a 6000 Å vacuum-deposited aluminum thin film. Referring to paragraph 3.6, the pattern scaling parameters are:

$$\epsilon = 0.18 \text{ and } R = 0.5147 \text{ inches}$$

so that the outside and inside pattern diameters are 1.400 and 0.658 inches, respectively. A continuous band of metal is left around the outer edge of the pattern. This serves as a useful electrode for either a ground reference potential or for aligning the eccentricities during tests of the standard pattern. A metallizing contact is plated over the edge of the substrate to attach this outer band to suitable lead wire that is soldered to the metallizing on the back of the substrate. A patch of metallization that provides a convenient pattern center was left in the center of the substrate. Intersecting lines that identify pattern center were put into the mask, and are etched in this metal when the pattern is etched. These lines provide a target for optical centering of the pattern in the test fixture during initial setup. This standard pattern set is shown in figure 7, installed in the test fixture adapter rings.

4.6 0.9-INCH DIAMETER STANDARD PATTERN SET

The 0.9-inch diameter standard pattern set is also fabricated on a 1.5-inch diameter quartz disc and the processing steps, with one exception, are identical. Specifically, the metal band that is outside of the pattern is much wider now because the outer pattern diameter is only 0.85 inches, referring again to the scaling of paragraph 3.6. In the 0.9-inch diameter standard pattern set, the outer metal electrode is connected to metallization on the back of the substrate through a metallized hole, as are the pattern and pickoff elements, so that no metallizing extends around the edge of the substrate. Other than for that detail, the two sets are processed identically, and differ only in the pattern scaling. The 0.9-inch diameter standard pattern and pickoff set is shown in figure 7.

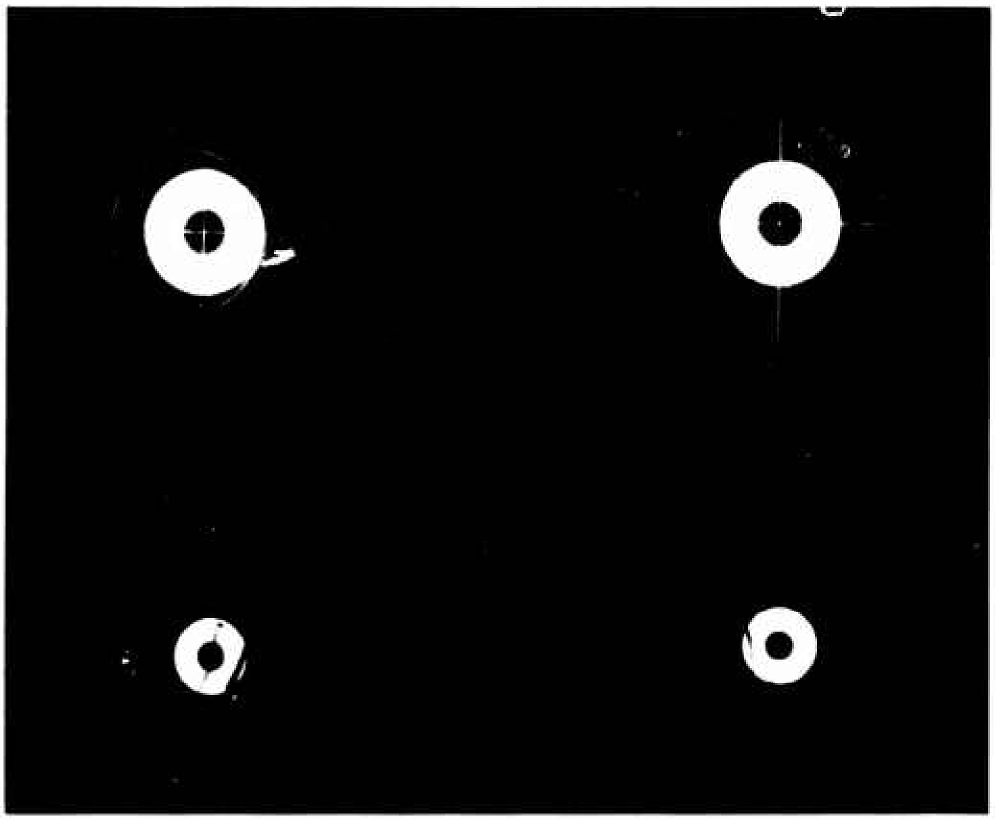


Figure 7. 1.5-Inch and 0.9-Inch Diameter Standard Patterns and Pickoffs

SECTION V

TEST FIXTURE DESIGN AND FABRICATION

5.1 GENERAL

This section discusses the mechanical test fixture that was developed to evaluate the various resolver pattern and pickoff elements. A Gertsch precision turntable was specially modified for this purpose.

5.2 GERTSCH RESOLVER TURNTABLE

The mechanical test fixture was built up around a small Gertsch precision resolver turntable. This turntable is shown (with the test fixture in place) in figure 8, and the rotational elements are shown schematically in figure 9. A shaft is supported in bearing plates which comprise the upper and lower covers of the turntable housing. A large notched disc is fixed to the shaft, and a pin detent is spring-loaded into these V-shaped notches (72 of them) which allows the shaft to be rotated in precise 5-degree increments. The shaft is hollow, and a tapered collet is fitted into its upper end, while a draw bar mechanism to tighten the collet is below. The collets vary in size up to 5/16-inch diameter, covering the range of resolver shaft sizes, and are identical to those used in small instrument-making machine tools. A second set of bearings, on the outside of the upper end of the shaft, support a platform which rotates to a limited degree around the shaft.

A dial indicator is mounted to the upper cover adjacent to the screw. This measures the small displacements imparted to the platform by the screw and converts them to angular measure. The collet appears in the center of the platform, and has full rotational freedom (in 5-degree increments) relative to both platform and housing. The platform, supported by the shaft, is constrained to small rotations relative to the housing (continuously variable up to plus or minus 3 degrees). The shaft is positioned, in 5-degree increments, to within 5 arc seconds true position, and the indicator (a modified 0.0001-inch instrument) is scaled to 6 arc seconds least count.

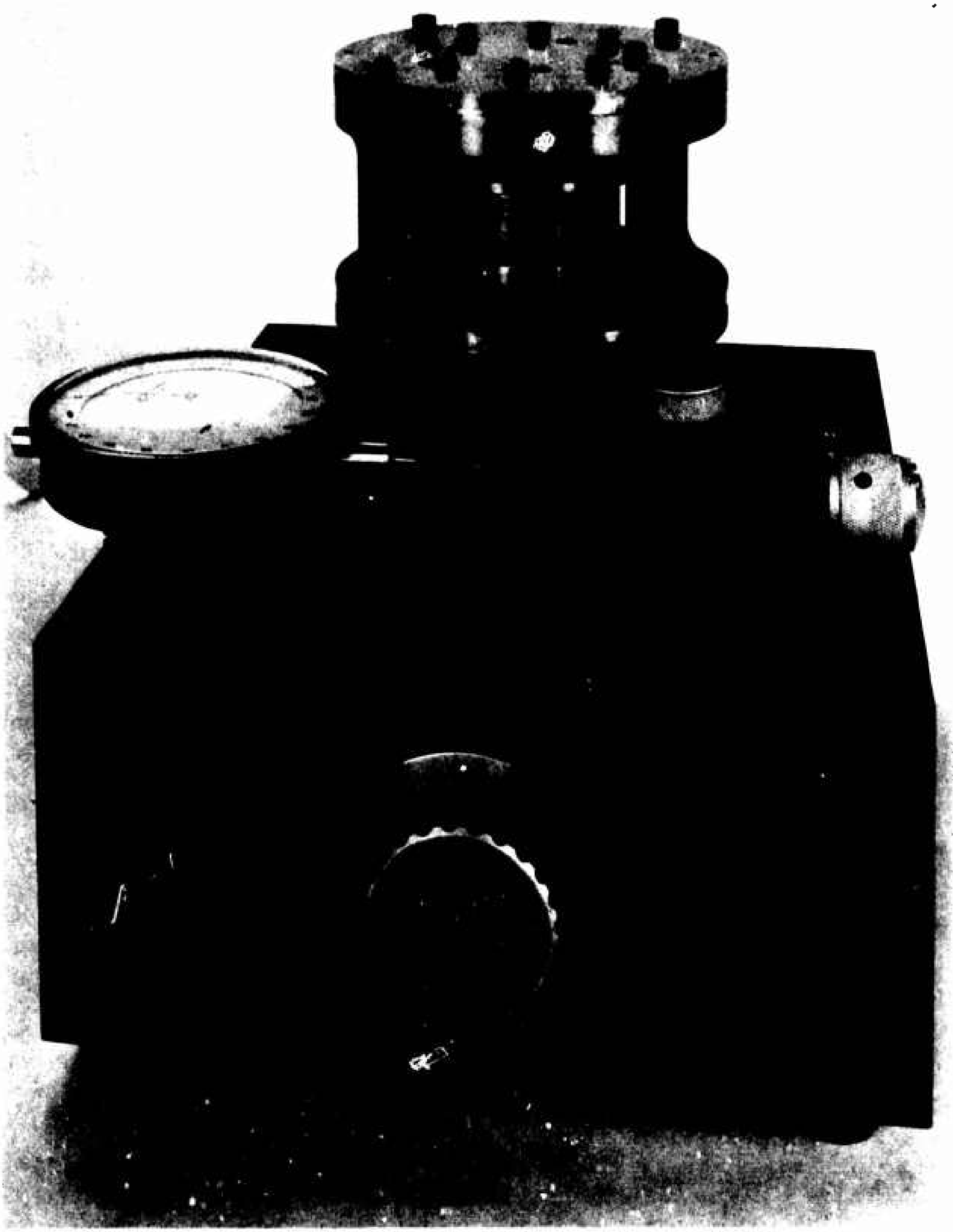


Figure 8. Gertsch Turntable and Test Fixture Prior to Modification

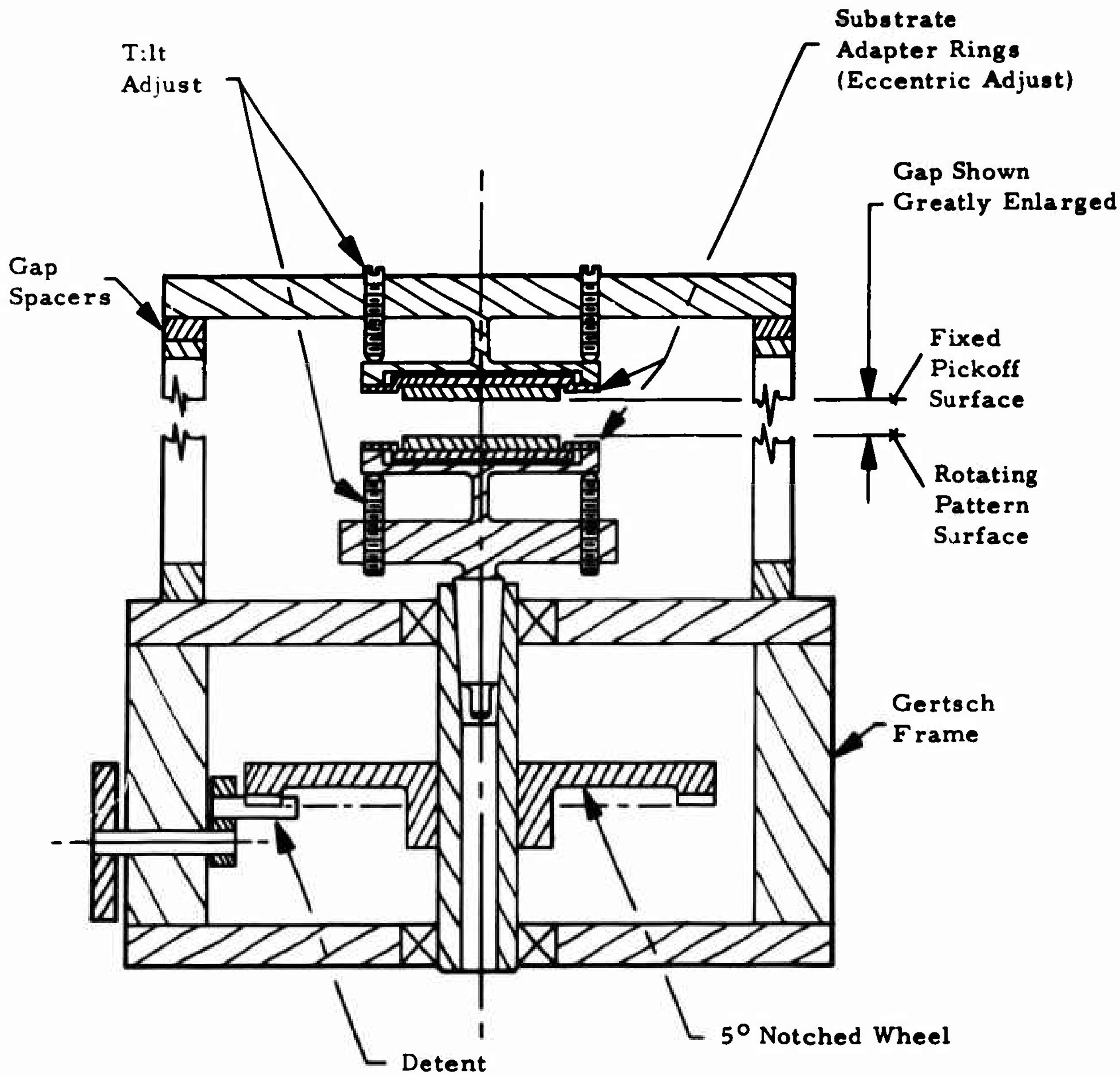


Figure 9. Schematic Diagram of Test Fixture

5.3 TEST FIXTURE

The test fixture was designed to adapt elements of the capacitive resolver to the Gertsch turntable so that precise rotations could be set up between the pattern and pickoff plates. The design allows adjustments to reduce initial misalignments of the axes of rotation for the pattern and pickoff, while these same adjustments allow the insertion of known misalignments during the course of the testing. Referring again to figure 9, the test fixture is seen to be made up of two similar mechanical structures, one attached to the shaft of the turntable, and one supported from the platform of the turntable. In each case the resolver substrate was mounted in an adapter ring. The ring fits loosely in a cup, being positioned radially by four equally spaced adjustment screws which provide a centering feature. The bottom of the cup was thinned to increase its compliance, and is attached to its base through a thin stem, the whole thing resembling a champagne glass in shape. Four jack screws extend from the base and bear against the stiff cylindrical walls of the cup. These screws provide a leveling mechanism to the cup and,

of course, to the surface of the device mounted therein. The first version of the test fixture design included compound-eccentric adapter rings that would align the center of the pattern with the center of rotation of the shaft. However, this adjustment feature was found to be troublesome to use, due to the coupling between the tilt and centering mechanisms. Tilt was eliminated by leveling the substrate surface to a plane normal to the axis of rotation of the shaft. However, the mechanism imparts a displacement to the pattern in this normal plane, which is then reduced by rotation of the eccentric pair which, unless the pattern surface and similar mating surfaces in the eccentric pair are perfectly parallel, imparts more tilt to the surface, and so on. The rotation required in adjusting the eccentrics was eliminated (by eliminating the eccentrics) and a simple radial looseness was substituted. Only a translation of the adapter ring was required to center the pattern in a prealigned plane. The motions were uncoupled and initial pattern alignment became a routine procedure.

A second modification to the initial version of the test fixture took place at the same time, and was due to the same problem, coupled mechanical adjustments. At first, the capacitive gap between the pattern and pickoff surfaces was to be set by the same jack screws that are used for leveling. This adjustment proved troublesome, and was replaced by the more direct method of installing spacers between the test fixture frame and the plate carrying the upper adjusting mechanism. These spacers are simple washers which have been surface ground in large sets, and then selected in groups of four, such that each washer in the set is within 50 millionths of an inch thickness of the other members of that set. At the same time, the centering adjustment for the "upper half" was moved to the spacer interface. The entire assembly was then displaced (in the plane of the spacers) relative to the outer frame, to which it was pinned initially.

5.4 MODIFICATION TO TURNTABLE

Two modifications to the Gertsch turntable were made during the first pattern testing phase of the program. The collet mechanism was replaced with a standard machine taper, and the platform and related adjustment screw and dial indicator were removed.

The collet mechanism was unstable because the clamping arrangement included a transverse pin that actuated a draw bar extended up through the shaft to the collet into which it was threaded. This draw bar mechanism, along with the funnel mouth shape of the collet receiver at the upper end of the shaft, did not exert enough force to tighten the collet adequately, or at least tighten it enough to support the "lower half" of the test fixture. The collet was removed and the funnel was remachined to a Morse No. 2 machine taper. The test fixture was reworked to provide a male taper at its base, instead of the original 5/16-inch shaft. This proved to be a stable joint throughout the test phases of the program.

The second problem proved to be more subtle. The turntable was designed to impart accurate rotations to devices that, for the most part, were supported in their own cases and on their own bearings. Therefore, while precision angular displacements can be expected, radial stability between the shaft and platform cannot. With its constraints removed, the platform becomes simply another bearing supported wheel on the shaft, which itself is bearing supported. The result is a built-in compound eccentricity between the platform and the shaft, unless the bearing installations (four of them) cancel all eccentricities both in the machining of bearing journals and in the bearings themselves. This is not likely. This eccentricity problem was identified when the first test data were reduced to Fourier coefficients, and the sense of a large two-speed error term could not be accounted for by considerations of the simple error model. Since the turntable precision was determined by the shaft positioning detent assembly and not by the fine adjustment features of the platform, it was decided to remove the platform entirely, and attach the test fixture outer frame directly to the upper housing cover of the Gertsch table. Pattern data were to be taken at 5-degree intervals, in any event, and the fine zero adjustment feature provided by the platform was not required. At the same time, the Gertsch housing was completely overhauled, the shaft bearings were replaced and suitable axial clearances were re-established to ensure adequate preload on this set of bearings.

The test fixture in its final form is represented by the schematic of figure 9, and is shown in figure 10. The 1.5-inch diameter and 0.9-inch diameter standard patterns, and the 0.9-inch diameter engineering model of the capacitive resolver are each mounted in adapter rings which, in turn, present a common interface to the test fixture.

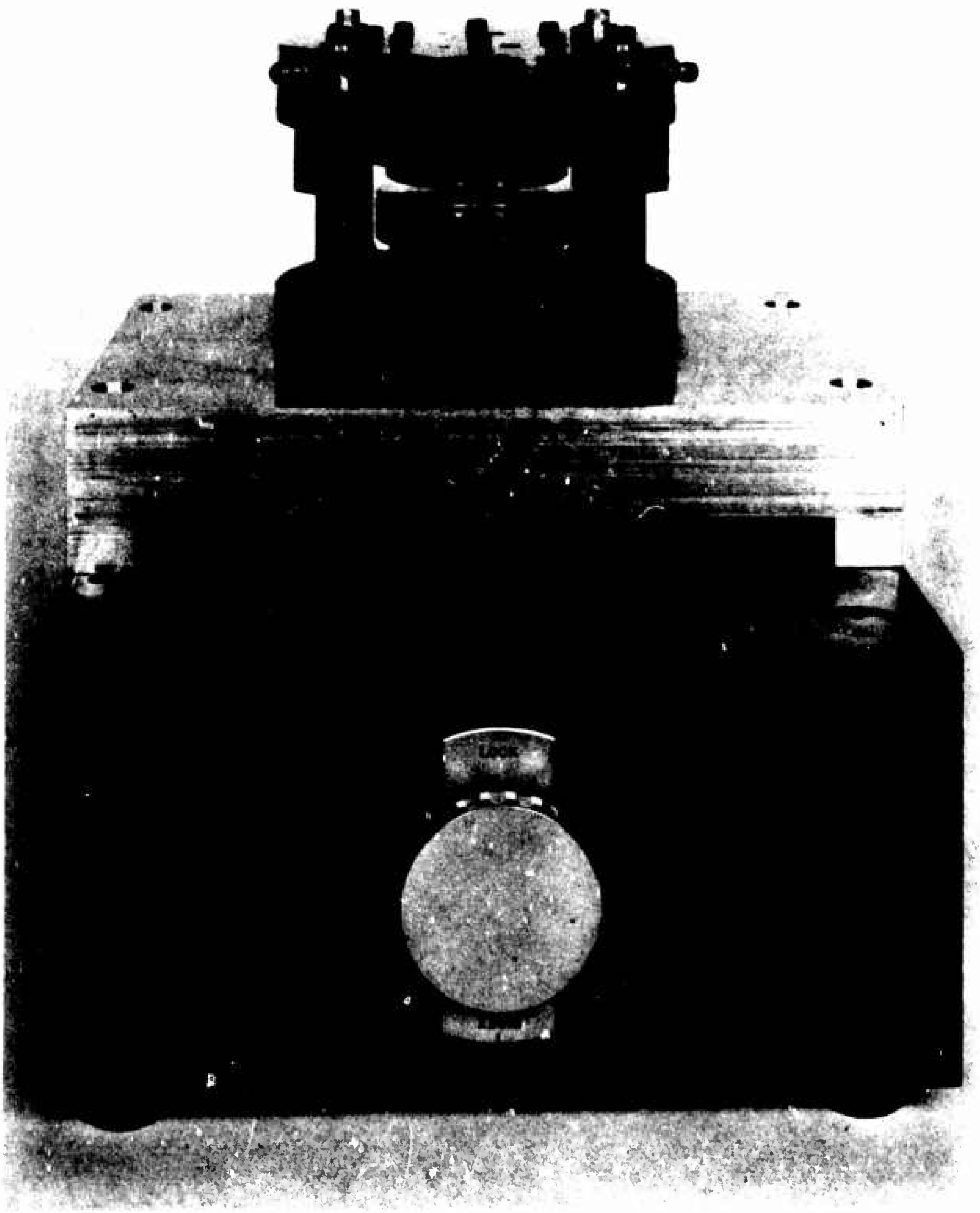


Figure 10. Modified Gertsch Turntable and Test Fixture in Final Form

SECTION VI

PATTERN PERFORMANCE TESTS AND DATA REDUCTION

6.1 SCOPE

This section presents details of pattern performance tests and data reduction. The electrical measurement system accompanying the mechanical test fixture is outlined, together with the various operating modes. There is an extensive discussion of the data reduction systems and the computer programs used. Note here the capability for deliberate introduction of errors into the test fixture and the study of their consequent effect on device accuracy. The test results for 1.5-inch and 0.9-inch diameter patterns are given.

6.2 TEST METHOD

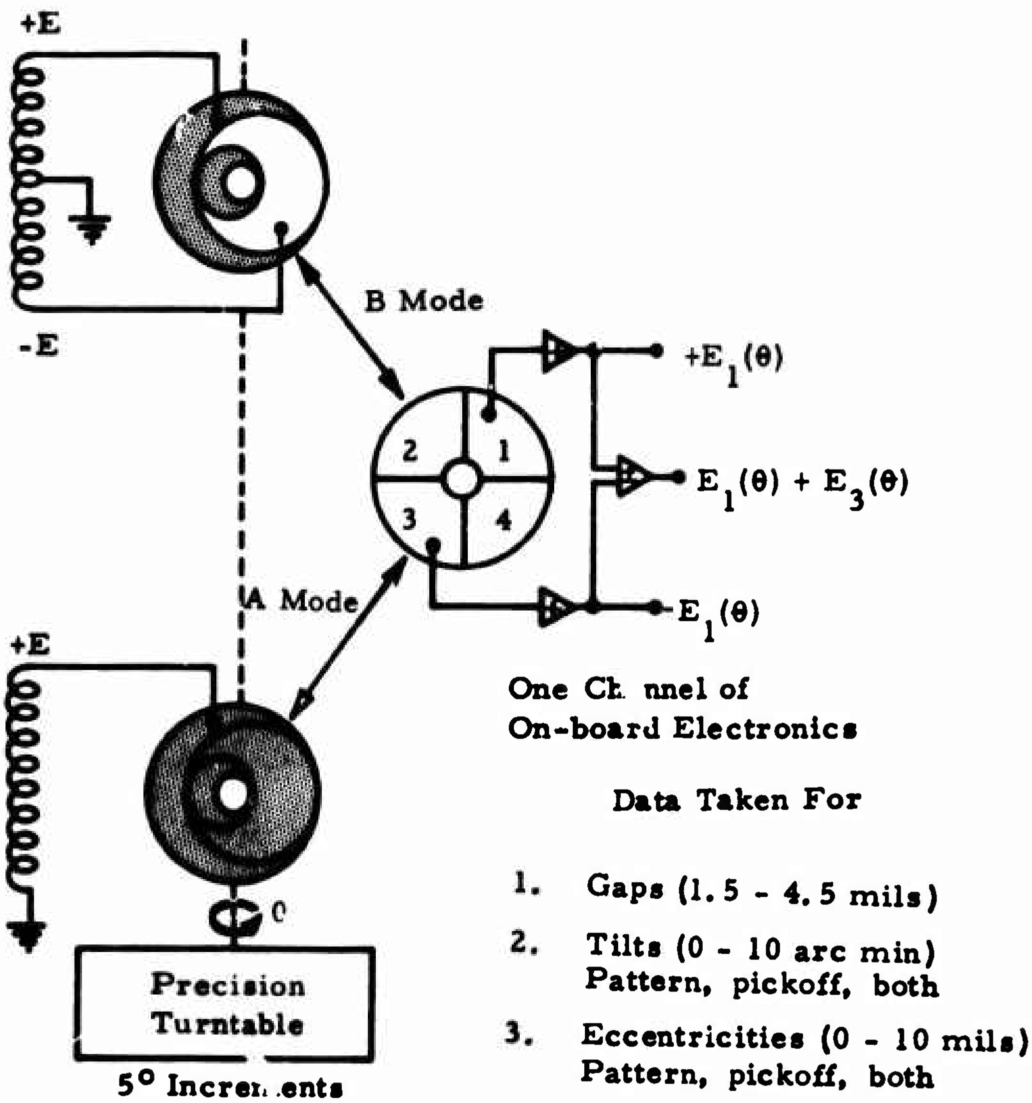
The requirements for a test method were defined early in the capacitive resolver program. The test method must examine and provide quantitative statements that measure the effectiveness of the experimental work which comprises the core of each developmental task in the program. It should be consistent with and complementary to the design and evaluation of pattern and pickoff, integral electronic processing circuitry and elements of the engineering model. It should also evaluate both the electronic and mechanical apparatus that is used throughout the testing and also be consistent with the design goal for device accuracy, ten arc minutes of angle.

The test method chosen evolves from two decisions:

a. All electrical measurements of pattern performance are at 100 Khz. Signal voltage measurements are peak-to-peak.

b. All data related to relative pattern and pickoff displacement are reduced to Fourier coefficients.

These two constraints, taken with the common data format that they imply, provide a maximum amount of correlation between various phases of development for the 0.9-inch diameter capacitive resolver. The test method scheme is illustrated in figure 11.



Raw Data

	A Mode				B Mode			
	1	2	3	4	1	2	3	4
1	$E_1(0)$	$E_2(0)$	$E_3(0)$	$E_4(0)$	$E_1(0)$	$E_2(0)$	$E_3(0)$	$E_4(0)$
2	$E_1(5)$	.	.	.	.	.	.	.
3	$E_1(10)$	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.
71	$E_1(350)$	.	.	.	.	.	.	.
72	$E_1(355)$	.	.	.	.	.	.	.
73	$E_1(360)$	$E_2(360)$	.	.	.	.	.	.

	B Mode	
	1-3	2-4
1	$E_{13}(0)$	$E_{24}(0)$
2	$E_{13}(5)$	.
3	$E_{13}(10)$	.
.	.	.
.	.	.
.	.	.
.	.	.
72	$E_{13}(355)$	.
73	$E_{13}(360)$	$E_{24}(360)$

Figure 11. Schematic and Block Diagram of Test Method for Capacitive Resolver Elements

6.3 TEST EQUIPMENT AND SETUP

A block diagram of the setup used for all data collection in this work is shown in figure 12. The a-c excitation signal for the resolver pattern is obtained directly from a General Radio 1650A impedance comparator, which contains a 100 Khz oscillator and delivers this signal to the outside through a transformer whose low-impedance secondary winding is very well balanced on either side of the grounded midpoint. The open-circuit voltages available here are balanced in amplitude to within 1 part in 10^6.

It is desired to be able to test the resolver system under two operating conditions:

a. Measure the voltages on each of the four pickoff plates separately, and process them with the desired programs.

b. Electrically sum the signals from opposite quadrants and process the result.

For a, the voltage is picked off from the desired plate and applied to the buffer amplifier described below. For case b, a signal processing amplifier, identical in electrical design to that discussed in section VII, is available. It differs from the hybrid circuit of section VII only in that it is built up of conventionally wired discrete components. Its output is also applied to the buffer amplifier when it is used. The final engineering model of the capacitive resolver is, of course, checked with its integral electronics package for signal processing instead of this outboard electronics package.

To make rapid, precise measurements of the signal voltages, an oscilloscope is used as a high-resolution null indicator, and amplitudes are determined as d-c voltages read from a precision digital voltmeter. The oscilloscope (any in the Tektronix 53- or 54- series) is provided with the type 1A1 plug-in vertical amplifier unit, which has the capability of accurately displaying signals from d-c through the megahertz region with a sensitivity of 5 millivolts per centimeter deflection under the condition that the peak-to-peak amplitude of the signal may be many times the total displayed amplitude. This excellent overload capability means that the oscilloscope may be used as a "slideback" voltmeter in which a known d-c voltage is added to the a-c signal under study to "slide-it-back" to a known reference point.

For example: a one volt peak-to-peak sinusoid is applied to the oscilloscope, with the trace previously centered on the vertical axis with vertical sensitivity at 5 millivolts per division. Both peak amplitudes are well off the screen. Adding a plus 500-millivolt d-c signal will bring the negative peaks to the center of the screen and, similarly, a minus 500-millivolt d-c signal will display the positive peaks of the applied signal. The peak-to-peak signal voltage is thus the difference of two digital voltmeter readings. This system is easily capable of reading to the nearest millivolt, and thus is capable of 0.1 percent resolution with typical signals of about 1 volt, peak-to-peak.

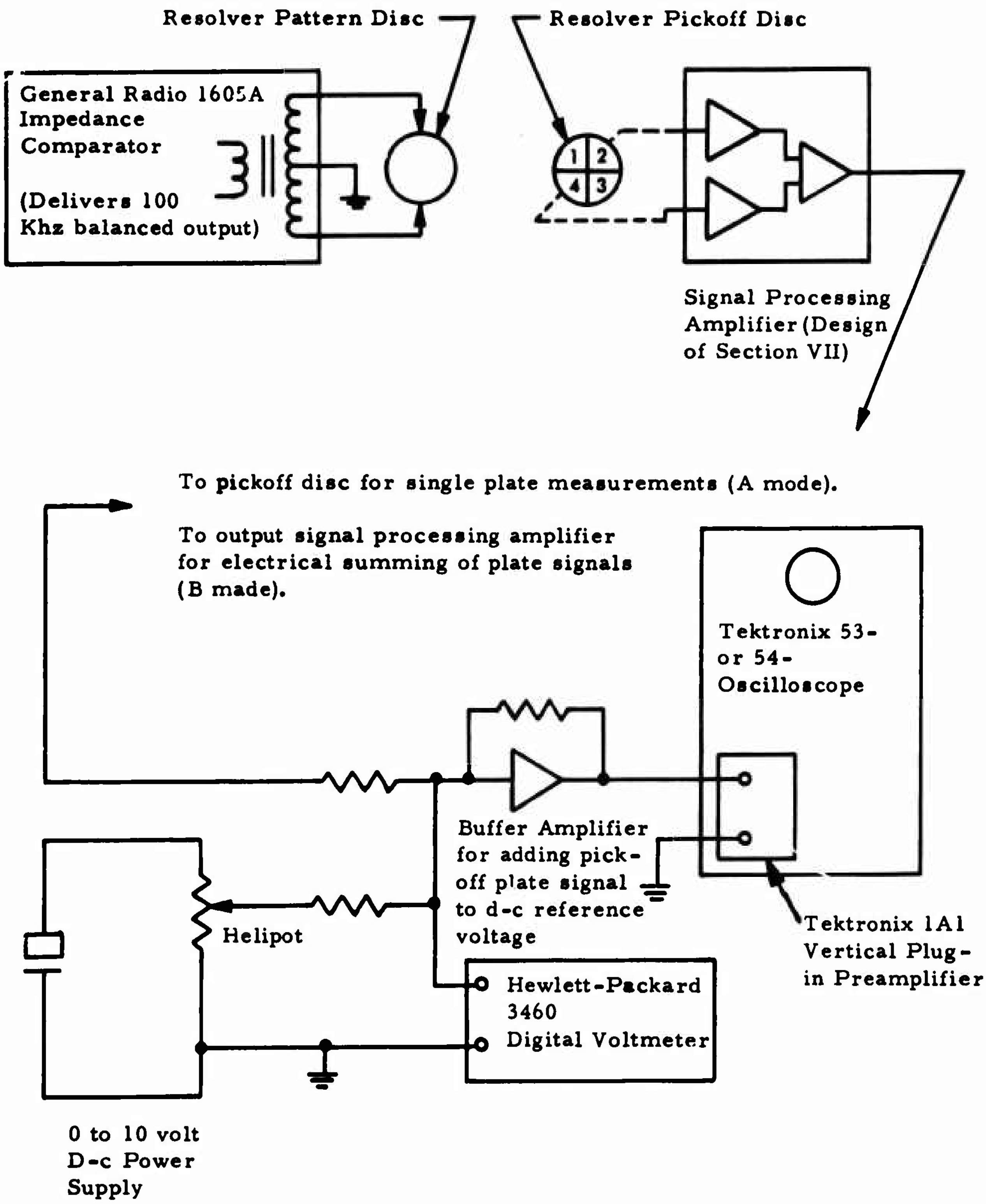


Figure 12. Electrical Test Setup for Capacitive Resolver Measurements

A d-c supply of a few volts is used here and a Helipot with a switched resistive voltage divider enables precise setting of the reference voltage. An operational summing amplifier is used as a buffer so that the pickoff plate signals and the d-c source do not load each other and interact.

6.4 MEASUREMENTS OF DEVICE PERFORMANCE AND DATA

Performance of the capacitive resolver is derived from a single point of measurement; the output signal of a pickoff quadrant. This output signal is measured for various combinations of pattern and pickoff topology and for different conditions of setup and alignment. Data are taken in the same sequence and in the same format for each combination.

6.4.1 Modes of Operation

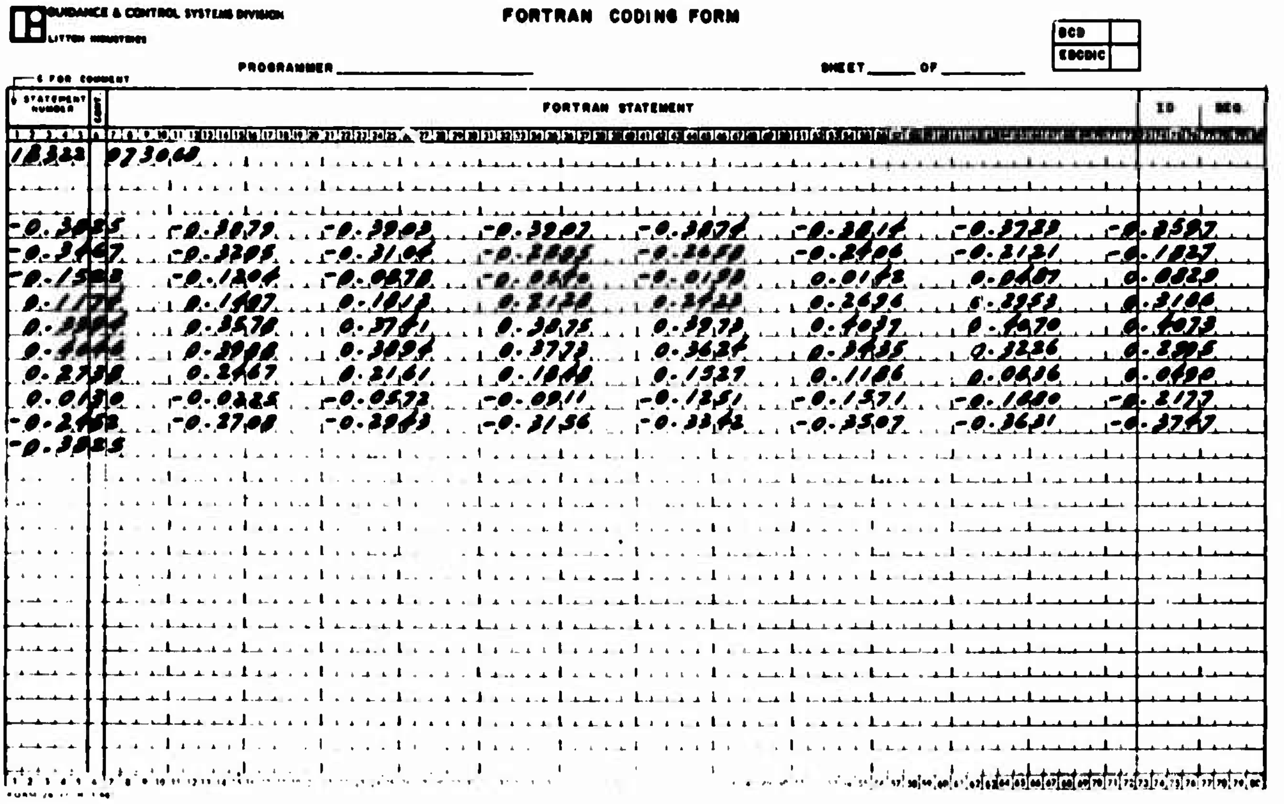
Output signal measurements are taken for two modes of pattern excitation. In the first of these, A mode, the elements of the pattern are excited from the same voltage and, in theory, the pattern disappears and only an annulus (or washer) remains. In the second, B mode, the outer and inner elements of the pattern are excited from one end of a balanced supply voltage and the central pattern element is excited from the other. A complete set of data is taken for each mode of excitation so that error producing anomalies in the mechanical apparatus can be separated from errors produced by the pattern.

6.4.2 Data Format

Output voltage measurements are taken at 5-degree intervals of angular displacement between the pattern (rotating) and the pickoff (fixed). The voltage is then measured at 73 points. The end point is the starting point and a comparison of these two voltages provides an indication of drift in the instrumentation. Agreement is typically within one millivolt. This set of voltages is measured for each of the four pickoff quadrants, for each mode of excitation. It is read from a digital voltmeter and is entered on Litton Form 26-07 (R11-66), a FORTRAN coding form that is arranged in punched card imagery (see figure 13). Cards are punched directly from this format (see figure 14). Eight sets of cards contain the data for each setup, one set for each pickoff quadrant, in both the A and B modes.

6.5 DATA REDUCTION

The data are processed by digital computer routines. First, they are reduced to a set of Fourier coefficients where they are screened for instrumentation/operator error. These coefficients are processed in a routine which subtracts the signals from opposite plates. Then the average angular bias is determined, and the coefficients are rotated through that bias angle. Finally, the desired signal, either sine or cosine, is separated and the remainder, which is designated error, is searched for a maximum. Two computer programs were written to accomplish this data reduction, one to


GUIDANCE & CONTROL SYSTEMS DIVISION
LITTON INDUSTRIES

FORTRAN CODING FORM

PROGRAMMER ______ SHEET ____ OF ____

12322	073060						
-0.3[illegible]5	-0.3079	-0.3902	-0.3202	-0.3074	-0.3014	-0.2722	-0.2597
-0.3[illegible]7	-0.3205	-0.3104	-0.2805	-0.2650	-0.2406	-0.2121	-0.1827
-0.15[illegible]	-0.1204	-0.0870	-0.0540	-0.0190	0.0148	0.0487	0.0829
0.1[illegible]	0.1407	0.1812	0.2120	0.2420	0.2696	0.2953	0.3106
0.[illegible]	0.3570	0.3761	0.3875	0.3972	0.4037	0.4070	0.4073
0.[illegible]	0.3900	0.3094	0.3772	0.3624	0.3435	0.3226	0.2995
0.27[illegible]	0.2467	0.2161	0.1846	0.1527	0.1186	0.0836	0.0490
0.01[illegible]0	-0.0225	-0.0572	-0.0911	-0.1251	-0.1571	-0.1880	-0.2177
-0.2[illegible]	-0.2708	-0.2963	-0.3156	-0.3342	-0.3507	-0.3631	-0.3747
-0.3[illegible]5							

Figure 13. Specimen of Format for Test Data Entry

reduce the raw data to Fourier coefficients and screen them, and one to sum opposite plates, rotate through the bias angle, separate the desired function, and evaluate the remaining error. The data reduction scheme is shown in block form in figure 15.

6. 5. 1 Fourier Analysis of Data: Program DFFOUR

The computer program for calculating the coefficients of a Fourier series that approximates the output function of the capacitive resolver is called DFFOUR, and is stored in the IBM RACS System 360 user file at the Litton Woodland Hills, California facility. The program was written specifically to process raw test data, in the format described above. The reduction to Fourier coefficients follows the method of harmonic analysis outlined by Sohon [1], and a set of data is processed through the following steps.

[1] Sohon, Harry, Engineering Mathematics, D. Van Nostrand Co., 1955 Pages 135, 145. A discussion of numerical methods for Fourier analysis.

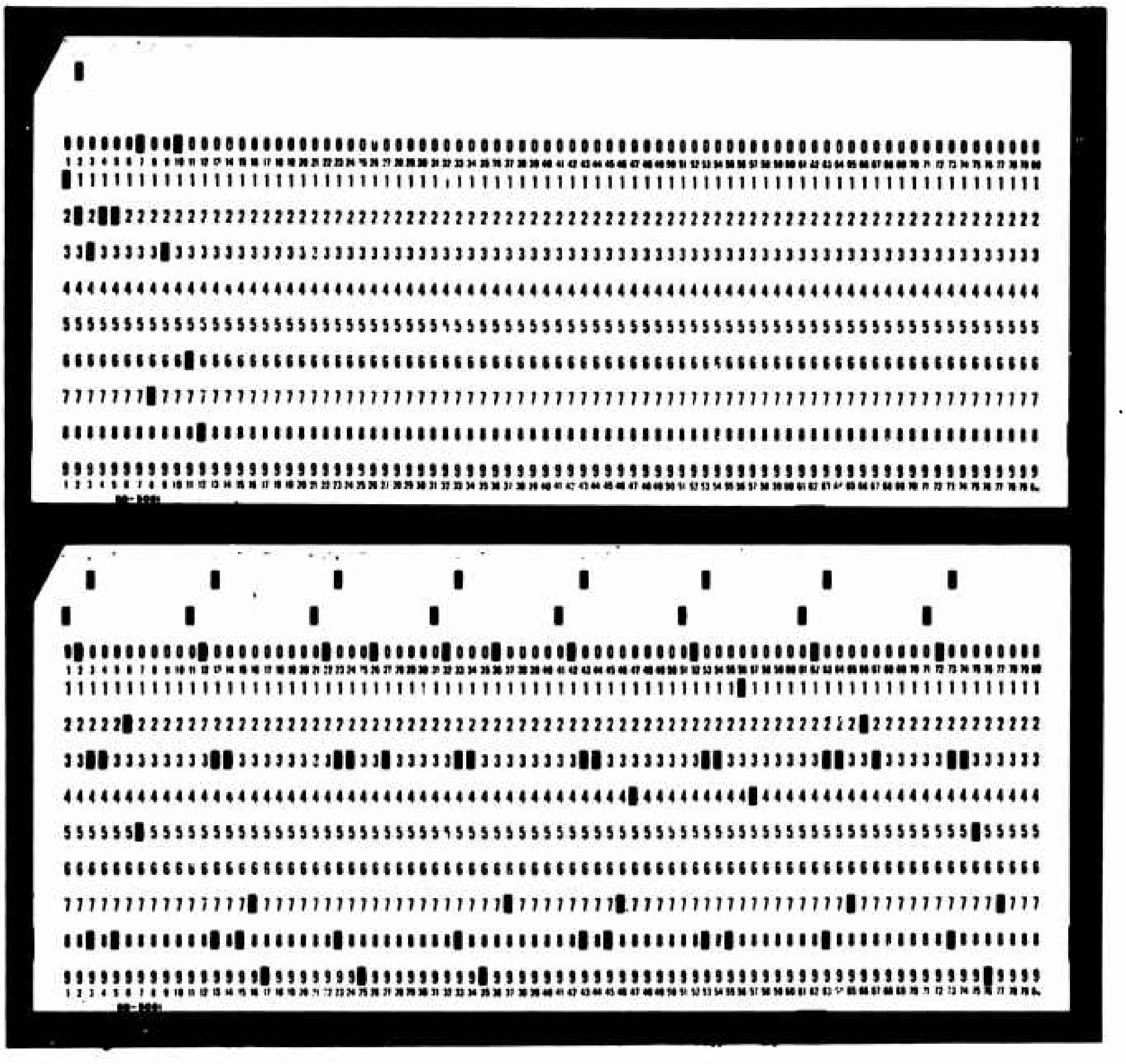


Figure 14. Specimen Format of Test Data Punched Card

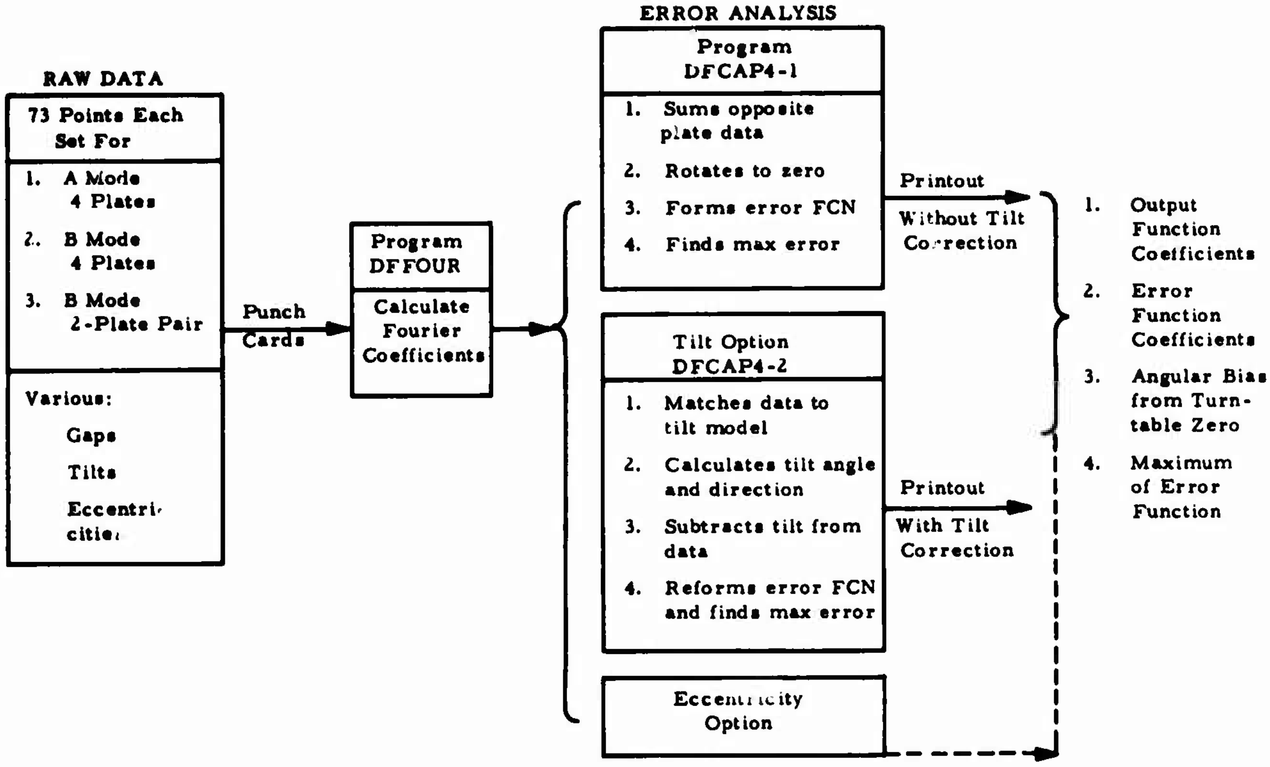


Figure 15. Block Diagram of Data Reduction Scheme for Capacitive Resolver Elements

a. Fourier coefficients are calculated from the raw data. The number of coefficients calculated is controlled in an input to the program, the interger M, which specifies the number of pairs.

b. A function is regenerated from the (M) pairs of coefficients, and the data are compared to the function at each data point. A standard deviation, σ, is calculated from this set of differences, and the data are examined to find points that differ from the function by more than 3σ.

c. Those data points which fall outside the 3σ screen are replaced by the value of the regenerated function at that point, one by one, the largest first, and the resulting data set (with one point exchanged) is returned to the routine which calculates Fourier coefficients. This screening continues until all 73 points are inside the 3σ band. Each time a substitution is made, an error indicator, designated IER, is incremented, and the final printout of coefficients includes this IER value, as well as the final standard deviation (σ), designated ENORM, and the maximum difference of any point from the mean, designated ANORM.

A specimen of the printout of DFFOUR is shown in figure 16. The alphanumeric group designates the elements being tested, the test mode, the capacitive gap, and the date the data were taken. The error indicator starts at 5, so that IER = 6 indicates that one piece of data had been replaced. The maximum value of the index K indicates the number of pairs of coefficients requested in the input control statement.

```
ANORM= 7.760E-04, ENORM= 3.015E-04, IER= 6


RUN NUMBER=1B322 073068


K        A(K)          B(K)

1    0.0023774     0.0
2   -0.3900706    -0.0859225
3    0.0044835     0.0047115
4    0.0002665    -0.0001477
5    0.0001895    -0.0000475
```

Figure 16. Specimen of Program DFFOUR Output Format
Control Statements: M = 5, IER = 5

A second option of program output can be implemented; that of printing the input data point adjacent to its difference from the regenerated function at that point, suppressing the 3σ screen and any substitution. This option, when run after the first, identifies those rejected data points by inspection. The option control character is IER again, and this latter option is implemented when IER is set to 2 in the program control. A specimen of this output format is shown in figure 16. Note that the coefficients are calculated from the raw data without substitution (for IER = 2), ANORM exceeds 3 ENORM as would be expected, and the coefficients are slightly different than for the first option, shown in figure 17. However, both are run from the same raw data, one with screening and substitution, and one without.

Both A mode and B mode data are reduced to coefficients with the DFFOUR routine.

ANORM= 1.031E-03, ENORM= 3.280E-04, IER= 2

RUN NUMBER=1B322 073068

I	A(K)	B(K)
1	0.002[illegible]918	0.0
2	--0.3900473	-0.0859061
3	0.0044933	0.0047384
4	0.0002591	-0.0001201
5	0.0001676	-0.0000291

I	FIN(I)	FOUT(I)
1	-0.3825000	0.0002355
2	-0.3879000	0.0001439
3	-0.3903000	0.0002303
4	-0.3907000	-0.0005183
5	-0.3874000	-0.0003994
6	-0.3814000	-0.0003947
7	-0.3723000	-0.0000690
8	-0.3597000	0.0010307
9	-0.3467000	-0.0001245
10	-0.3295000	0.0003555
11	-0.3103999	0.0002795
12	-0.2895000	-0.0003245
13	-0.2658000	-0.0003106
14	-0.2406000	-0.0008151
15	-0.2121000	0.0001405
16	-0.1827000	0.0003504
17	-0.1522999	0.0001204
18	-0.1204000	0.0001684
19	-0.0878000	-0.0000799
20	-0.0540000	0.0001101
21	-0.0198000	0.0001781
22	0.0142000	-0.0002304
23	0.0487000	-0.0001673
24	0.0829000	-0.0001807
25	0.1174000	0.0005817
26	0.1497000	-0.0001259
27	0.1813000	-0.0005516
28	0.2128000	0.0001559
29	0.2423000	0.0003424
30	0.2696000	0.0000487
31	0.2952999	0.0001061
32	0.3186000	-0.0000638
33	0.3394000	-0.0003551
34	0.3577999	-0.0004772
35	0.3741000	0.0000398
36	0.3875000	0.0005442
37	0.3972999	0.0004592
38	0.4037000	0.0000819
39	0.4069999	-0.0002191
40	0.4073000	-0.0003035
41	0.4046000	-0.0001608
42	0.3988000	0.0000905
43	0.3893999	-0.0000971
44	0.3773000	0.0001009
45	0.3624000	0.0004823
46	0.3435000	-0.0002809
47	0.3225999	-0.0003405
48	0.2995000	-0.0000717
49	0.2738000	-0.0000700
50	0.2467000	0.0006490
51	0.2161000	-0.0002473
52	0.1848000	-0.0002081
53	0.1526999	0.0004049
54	0.1186000	0.0001172
55	0.0836000	-0.0002526
56	0.0490000	0.0003067
57	0.0130000	-0.0002954
58	-0.0225000	-0.0004496
59	-0.0572000	-0.0001417
60	-0.0911000	0.0003486
61	-0.1251000	-0.0001470
62	-0.1571000	0.0002152
63	-0.1880000	0.0002960
64	-0.2176999	-0.0000277
65	-0.2452000	0.0000413
66	-0.2708000	0.0000187
67	-0.2943000	-0.0000588
68	-0.3156000	-0.0002358
69	-0.3342000	-0.0001366
70	-0.3507000	-0.0004686
71	-0.3631000	0.0006790
72	-0.3747000	-0.0000671
73	-0.3825000	0.0002354

Figure 17. Specimen of Program DFFOUR Output Format Control Statements: M = 5, IER = 2

6.5.2 Summation of Opposite Quadrant Signals: Program DFCAP4

Four sets of coefficients are processed in a computer routine which sums the opposite quadrant signals, two for the cosine channel and two for the sine channel, and represents computationally the same signal processing that occurs in the electronic summing circuitry. This computer program is called DFCAP4, and is also stored in the RACS System 360 user file at Woodland Hills, California. The program implements the following data processing steps:

a. Fourier coefficients from B mode data sets are punched in cards. These cards, along with appropriate input control statements that identify the data and specify the number of coefficients being entered, initiate DFCAP4.

b. The four coefficient sets are ordered and examined for proper sense, and the coefficients from opposite plates are summed.

c. These summed pairs of coefficients are normalized on their principal terms, the root of the sum of the squares of the one-speed sine and cosine coefficients.

d. The angular bias, or zero offset, is calculated from the two one-speed pairs of coefficients. Note that the raw data are taken without any attempt to align "pattern zero," so that the sine plates coefficients and the cosine plates coefficients are used to calculate an average angular bias of the data by calculating the respective arctangents of the ratio of sine coefficient to cosine coefficient for each set of plates.

e. The coefficients are rotated through the average bias angle so that the principal component on the sine plate is one-speed sine with a minimum of one-speed cosine, and the principal component on the cosine plate is one-speed cosine with a minimum of one-speed sine. Physically, this rotation is analogous to having a fine adjustment on the test fixture that allows the pattern zero to be aligned with the turntable zero, in an average sense, prior to making any measurments.

f. The normalized and rotated coefficients that now represent the output signals of the sine and cosine plates of the resolver are expanded into a set of "data" points, and compared to an exact sine or cosine function at each point. The point by point difference is designated as error in the output.

g. The error function is analyzed harmonically and reduced to a set of Fourier coefficients, which is printed in the output format.

A specimen output for DFCAP4 is shown in figure 18. The four sets of coefficients are identified in the alphanumeric fields under RUN NUMBER and TYPE, while the values of ANORM, ENORM, IER, and M from the four DFFOUR passes are printed out. The four sets of coefficients are printed out after ordering, sensing, and normalizing. The angular bias for each set is printed out below, and below them is the average bias, along with the spread in the angles, and a program error indicator, JER, which signals troubles in the earlier sensing and summing sequence, 5 being the acceptable value. The summed coefficients appear below, for both the sine and cosine plates, and below them, the maximum value of the error residue, and its angular locations. Finally, the coefficients of the error (residue) function are printed out.

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18131 080768 QT	0.9 STD	7.371E-04	2.350E-04	5	5	12311
18231 080768 QT	0.9 STD	8.352E-04	2.866E-04	6	5	12312
18331 080768 QT	0.9 STD	5.404E-04	2.430E-04	5	5	12313
18431 080768 QT	0.9 STD	6.763E-04	1.927E-04	5	5	12314

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.014004	0.0	-0.000255	0.0	-0.004269	0.0	-0.011253	0.0
2	0.987125	0.159953	0.202706	-0.979240	-0.969815	-0.243844	-0.199859	0.979825
3	0.000273	-0.002707	-0.014070	0.000784	0.007637	0.010110	0.001228	-0.006321
4	0.000354	0.000604	-0.000397	0.000964	0.000346	-0.000035	0.000566	-0.000849
5	-0.000250	0.000634	-0.000080	0.000292	0.000247	0.000191	0.000094	-0.000265

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-8.20 DEGREES -11.70 DEGREES -14.11 DEGREES -11.53 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.64 DEGREES, DIFFERENCE IN ANGLES = 2.343E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.009735	0.0	-0.011037	0.0
2	1.998165	0.000817	0.000818	1.999997
3	-0.011829	-0.008865	0.011242	-0.012581
4	0.000372	0.000520	-0.000248	0.002037
5	-0.000021	0.000666	-0.000285	-0.000509

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 6.79 ARC MINUTES AT 35.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000010	0.0
2	-0.000490	-0.001235
3	0.000222	0.000029
4	0.000355	-0.000323
5	0.000071	-0.000603

Figure 18. Specimen of Program DFCAP4 Output Format

6.5.3 Tilt Option in Program DFCAP4

During the program phase of initial standard pattern evaluation, it was felt that some, and possibly all, of the errors introduced into the test data by mechanical setup could be separated from errors originating in the pattern and pickoff topologies, or arising from fringing capacities. Each experimental setup had eight sets of correlated data associated with it (one set from each pickoff quadrant for each mode). These nearly 600 data points should provide some information about separable errors. The first of the mechanical error models to be analyzed was pattern tilt (which is discussed in section X). The tilt error model predicted a particular distribution of output error for each pickoff quadrant. This expected error is a function of the magnitude and direction of the tilt vector, and for small tilts, a linear combination of the two. A routine was added to the DFCAP program that compared the four sets of coefficients with their expected values in a least squares sense, and a best fit was selected from a search of values of the two parameters of the error model. When this best fit had been selected, the error components that were predicted by the model were separated from the coefficients, which were then summed, rotated, and examined for output error as before.

A specimen of the output format for this DFCAP4 tilt option is shown in figure 19 for the same input data used for figure 18. The results of the tilt error separation option were inconclusive, and this option was not used in evaluating standard pattern test data

6.6 DELIBERATE INTRODUCTION OF MECHANICAL ERRORS IN PATTERN TESTS

The test fixture that adapts the pattern and pickoff elements to a precision turntable features adjustments which reduce the two principal error producing mechanical misalignments, tilt and eccentricity, to an acceptable level. These two adjustments are used to introduce measured amounts of tilt and eccentricity into the testing, either singly or in combination, when the effects of these misalignments are being evaluated.

a. Two types of tilt are introduced.

  (1) Pattern tilt: This tilts the surface of the pattern away from plane normal to the axis of rotation of the pattern, in a specified direction from pattern zero.

  (2) Pickoff tilt: This tilts the surface of the pickoff away from the plane normal to the axis of rotation of the pattern, in a specified direction from the center of the cosine plates.

```
                         ---CAPACITIVE RESOLVER DATA REDUCTION---

          RUN NUMBER        TYPE          ANORM          ENORM          IFR        M      CODE

          1B131 080768 QT  0.9 STD     7.371E-04      2.350E-04         5          5      12311
          1B231 080768 QT  0.9 STD     8.352E-04      2.806E-04         6          5      12312
          1B331 080768 QT  0.9 STD     5.404E-04      2.430E-04         5          5      12313
          1B431 080768 QT  0.9 STD     6.763E-04      1.927E-04         5          5      12314

                  FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

            PLATE 1                    PLATE 2                    PLATE 3                    PLATE 4

K        A(K)       B(K)          A(K)       B(K)          A(K)       B(K)          A(K)       B(K)

1     -0.014004   0.0          -0.000255   0.0          -0.004269   0.0          -0.011293   0.0
2      0.987125   0.159953      0.202706  -0.979240     -0.969815  -0.243844     -0.199859   0.979625
3      0.000273  -0.002707     -0.014070   0.000794      0.007637   0.010110      0.001228  -0.006321
4      0.000354   0.000604     -0.000397   0.000964      0.000346  -0.000035      0.000566  -0.000849
5     -0.000250   0.000634     -0.000080   0.000292      0.000247   0.000191      0.000094  -0.000265

                      ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

        -9.20  DEGREES           -11.70  DEGREES           -14.11  DEGREES           -11.53  DEGREES

              MEAN BIAS ANGLE = -11.64 DEGREES,   SIGMA(BIAS ANGLE) = 1.737E 00 DEGREES

                         ---PATTERN AND PICKOFF TILT CORRECTIONS---

             RELATIVE TILT = -0.005104 WITH TILT AXIS AT  30.00 DEGREES FROM PATTERN ZERO

                    MINIMUM OF SUM-DIFFERENCE-SQUARES FUNCTION = 7.125E-04

                           FOURIER COEFFICIENTS CORRECTED FOR TILT

            PLATE 1                    PLATE 2                    PLATE 3                    PLATE 4

K        A(K)       B(K)          A(K)       B(K)          A(K)       B(K)          A(K)       B(K)

1     -0.011450   0.0           0.002299   0.0          -0.001715   0.0          -0.008738   0.0
2      0.987135   0.159893      0.202646  -0.979253     -0.969830  -0.243782     -0.199798   0.979838
3      0.002140  -0.002922     -0.015937   0.001010      0.009505   0.009894     -0.000640  -0.006105
4      0.000340   0.000603     -0.000395   0.000950      0.000360  -0.000034      0.000565  -0.000835
5     -0.000250   0.000634     -0.000080   0.000292      0.000247   0.000191      0.000094  -0.000265

                            ---OPPOSITE PLATE PAIR SUMMATION---

                      ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

        MEAN BIAS ANGLE = -11.63 DEGREES,  DIFFERENCE IN ANGLES = 2.343E-02 DEGREES,  JFR = 5

                          FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

                          COSINE PLATES                     SINE PLATES

                   K      A13(K)      B13(K)               A24(K)      B24(K)

                   1    -0.009735    0.0                 -0.011037    0.0
                   2     1.998164    0.000817             0.000818    1.999998
                   3    -0.011828   -0.008866             0.011243   -0.012579
                   4     0.000348    0.000534            -0.000234   -0.002013
                   5    -0.000021    0.000666            -0.000284   -0.000509

                      ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
                   MAXIMUM OF ERROR FUNCTION =  6.77 ARC MINUTES AT  35.00 DEGREES

                                  ERROR FUNCTION COEFFICIENTS

                             K        AER(K)       BER(K)  (IN RADIANS)

                             1      -0.000010     0.0
                             2      -0.000489    -0.001235
                             3       0.000222     0.000029
                             4       0.000355    -0.000323
                             5       0.000078    -0.000591
```

Figure 19. Specimen of Program DFCAP4 Output Format with Execution of Tilt Option

b. Two types of eccentricity are introduced.

(1) Pattern eccentricity: This displaces the pattern center away from the center of rotation of the pattern, in a specified direction from pattern zero.

(2) Pickoff eccentricity: This displaces the center of the pickoff (quadrants) away from the center of rotation of the pattern, in a specified direction from the center of the cosine plates.

Another class of error producing mechanism has been included in the testing pattern and pickoff anomalies. These anomalies arise from defects in the metallization, or from holes or other local defects in the substrates that will introduce anomalies in the electric field distribution between the pattern and pickoff.

In each case, the data are identified in the column labled "TYPE" in the output formats of DFFOUR and DFCAP4.

6.7 SUMMARY OF TEST RESULTS

Two sets of standard patterns were evaluated, a 1.5-inch diameter pattern and pickoff, and a 0.9-inch diameter pattern and pickoff, both fabricated on 1.5-inch diameter by 0.15-inch thick fused quartz substrates. A third set of 0.9-inch diameter units with 0.020-inch diameter holes that were metallized to connect the pattern/pickoff metallization to the back of the substrates was also evaluated.

6.7.1 1.5-Inch Diameter Standard Pattern

Five sets of test data were taken on the 1.5-inch diameter standard pattern and pickoff, three without tilt, and two with deliberate tilts introduced. The results are summarized in table I. On the basis of these test data, it was decided to make a direct scaling reduction to the 0.9-inch diameter standard, without changing the shape of the pattern.

6.7.2 0.9-Inch Diameter Standard Pattern

Thirteen sets of test data were taken on the 0.9-inch diameter standard pattern and pickoff, eight with deliberate misalignments, and five without. The test results are summarized in table II.

6.7.3 0.9-Inch Patterns with Holes

Five sets of test data were taken on a pair of 0.9-inch pattern and pickoff substrates which used 0.020-inch diameter metallized holes to connect the pattern and pickoff elements to the opposite side of their respective substrates. In the previous standard pattern testing, these holes had been filled with a metal plug brought flush to the surface of the pattern/pickoff

TABLE I. SUMMARY OF TEST RESULTS FOR 1.5-INCH DIAMETER STANDARD PATTERN

Date	Gap (Mils)	Max Error (Arc Minutes)	Mechanical Misalignments
6/27/68	2.8	35.1	None
7/3/68	1.9	8.8	None
7/8/68	3.6	9.0	None
7/16/68	3.6	10.7	Pickoff (fixed) tilted
7/17/68	4.0	25.8	Pattern (rotates) tilted

metallization. In this set of tests, however, the holes were left unfilled to determine whether these "local defects" in the metallized surfaces would introduce measurable errors. They did not and the results are summarized in table III.

The final three sets of data in this group were taken with the breadboard of the finalized electronic processing circuitry attached to the test fixture. The output signals of opposite pickoff quadrants are being summed electronically for the first time, and the resulting "channel" output is processed through DFFOUR and DFCAP4 by entering the data in duplicate. The results are comparable to those obtained by looking at each plate separately, then synthesizing the summation with the computer routine.

6.7.4 Pattern Specification for Engineering Model

Examination of the last three sets of test data from the 0.9-inch "standard pattern with holes" shows that the pattern/pickoff topology couples accurately enough to allow its use without modification for the fabrication of the engineering model of the 0.9-inch diameter capacitive resolver. The test results indicate also that the device can be gapped between 1.5 and 3.5 thousandths of an inch and its expected performance, with the hybrid microelectronic signal processing electronics, should meet the design goal of 10 arc minutes accuracy.

TABLE II. SUMMARY OF TEST RESULTS FOR 0.9-INCH DIAMETER STANDARD PATTERN

Date	Gap (Mils)	Max Error (Arc Minutes)	Mechanical Misalignments
7/24/68	4.2	24.6	None
7/26/68	2.7	9.0	None
7/30/68	2.2	5.3	None
8/1/68	1.6	9.3	None
8/5/68	3.3	8.8	None
8/7/68	3.1	6.8	Pickoff (fixed) tilt
8/9/68	3.3	15.2	Pattern (rotates) tilt
8/15/68	3.1	42.5	Pickoff (fixed) eccentric 6 mils
8/16/68	3.1	105.5	Pickoff (fixed) eccentric 10 mils
8/21/68	3.3	11.0	Pattern (rotates) eccentric 6 mils
8/22/68	3.3	11.3	Pattern (rotates) eccentric 10 mils
8/28/68	3.3	26.7	Pickoff (fixed) eccentric 6 mils toward sine plates
8/30/68	2.8	20.5	Pickoff (fixed) eccentric 6 mils toward cosine plates

TABLE III. SUMMARY OF TEST RESULTS FOR 0.9-INCH DIAMETER PATTERN WITH 0.020-INCH HOLES

Date	Gap (Mils)	Max Error (Arc Minutes)	Mechanical Mislignment	Remarks
9/17/68	2.9	6.6	None	Pickoff measured separately
9/24/68	1.8	9.1	None	Pickoff measured separately
9/27/68	1.8	7.9	None	Pickoff summed electronically
10/10/68	3.0	6.0	None	Pickoff summed electronically
1/30/69	2.3	6.4	None	Pickoff summed electronically

SECTION VII

ELECTRONICS REQUIREMENTS AND DESIGN

7.1 SCOPE

In this section, the possible signal processing options are evaluated and the choice of an operational amplifier approach is discussed. The detailed design is worked out, and some expected response curves given.

7.2 REQUIRED ELECTRICAL PERFORMANCE

The most general way to consider the requirements for the electronics portion of the miniature capacitive resolver is to discuss its three primary functions: (1) to match the input signals properly; (2) to process the signals, and (3) to deliver the processed signals to the outside world.

7.3 CONVENTIONAL VOLTAGE AMPLIFIERS: ADVANTAGES AND DISADVANTAGES

The input signals are 100-Khz sinusoids which are delivered from a constant amplitude source through a small capacitance, in the range of 1 to 20 pf, representing a source impedance of from 1.5 megohms to 80K ohms, respectively. From this large impedance, the first suggestion is to use a field effect transistor (FET) in the source follower configuration, as shown in figure 20. The pattern plates are fed with equal and opposite voltages of magnitude e_i, and their respective capacitances to the pickoff plate are C_1 and C_2. All of the stray capacitance to ground is combined into C_3.

The equivalent circuit is shown in figure 21. In this configuration, the gate source capacitance, C_{gs}, is reduced by the factor $(1 - A)$, where A, the voltage gain, is very close to unity, and thus C_{gs} can be disregarded. The gate-drain capacitance is not reduced in this simple configuration, and hence is lumped with C_3. The bias resistor, R_b, is assumed to be much larger than any of the capacitive reactances, and can be disregarded.

The actual voltage available at the FET gate, denoted by e_g, must first be determined in terms of the various circuit capacitances and the voltages

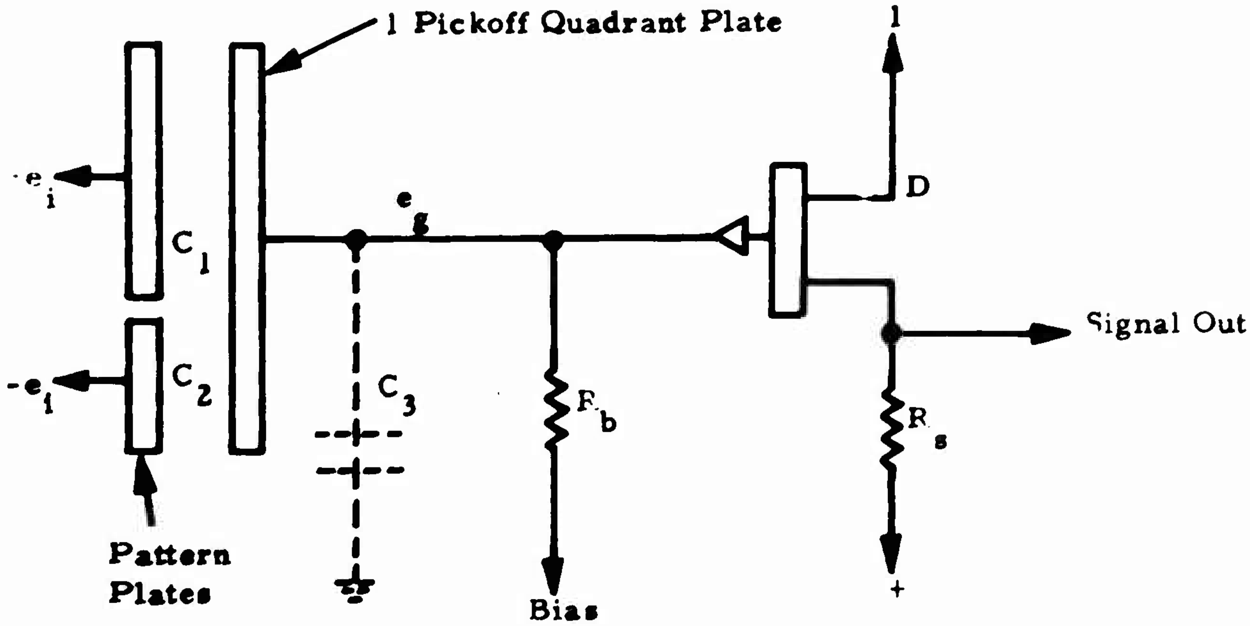


Figure 20. Source Follower Input Circuit for Electronics Package

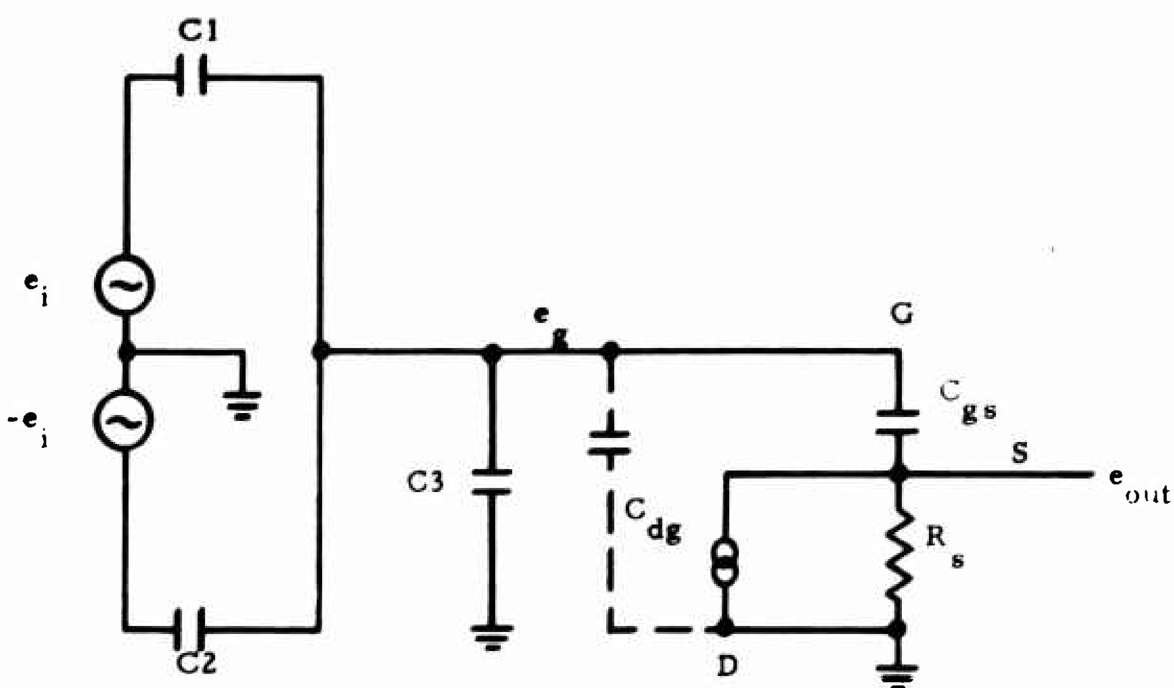


Figure 21. Equivalent Circuit for Source Follower Input

applied to the pattern plates. A straightforward way of doing this is by superposition, saying that e_o is the resultant of the three capacitors acting as a voltage divider upon e_i:

$$e_o = e_i \frac{Z_2 \| Z_3}{Z_1 + Z_2 \| Z_3} - e_i \frac{Z_1 \| Z_3}{Z_2 + Z_1 \| Z_3}$$

where Z_1 is the reactance of C_1 and the symbol $\|$ means "in parallel with". After some algebra, and replacing each Z with $1/\omega C$

$$\frac{e_o}{e_i} = \frac{C_1 - C_2}{C_1 + C_2 + C_3}$$

If there were no C_3, there would be no loading on the pickoff plates, and a "perfect" output voltage could be defined, which can be denoted by e'_o:

$$\frac{e'_o}{e_i} = \frac{C_1 - C_2}{C_1 + C_2}$$

The introduction of the stray capacitance, C_3, would cause an error term, a correction to e_o designated by Δe_o:

$$e_o = e'_o + \Delta e_o + \left(\Delta e_o\right)^2 + \ldots$$

$$\frac{\Delta e_o}{e'_i} = - \frac{C_3}{C_1 + C_2}$$

The disadvantages of this approach are immediately apparent. The error term is considerable, since C_3 can easily be as much as 3 to 5 pf, and the sum of C_1 and C_2 is only 10 pf for a 3-mil gap. Any changes in C_3 will result in a first order change in e_g.

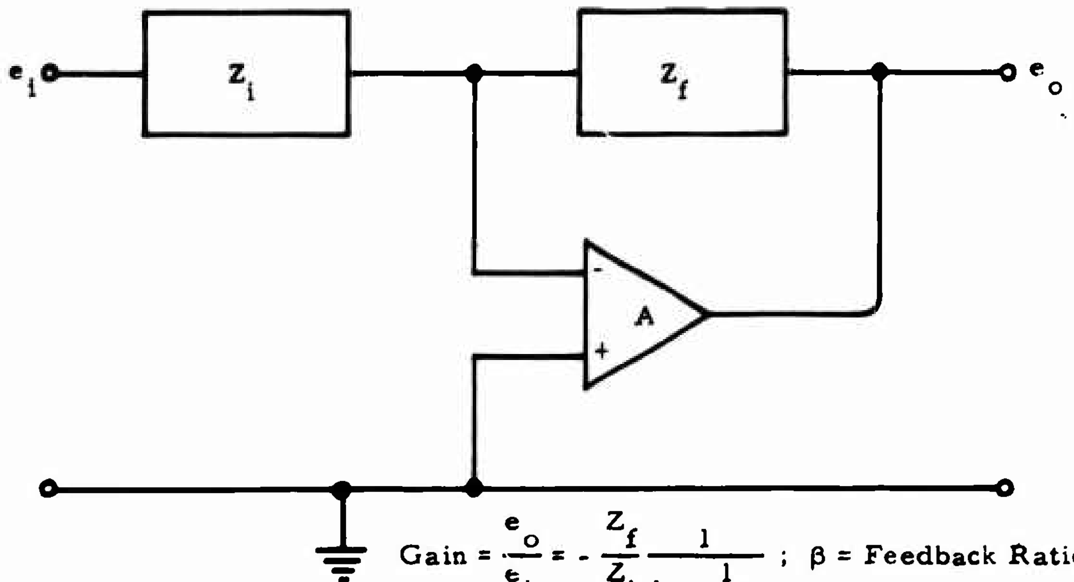
The other serious disadvantage of the voltage-follower approach is that the pickoff plates and the associated connections are at a high impedance level, and thus are very sensitive to stray pickup. Electrostatic shielding could reduce this pickup considerably, but would increase C_3 and further reduce the signal voltage. There would also be serious mechanical constraints on the shielding, since the least possible variation in C_3 is required as the resolver elements rotate.

7.4 OPERATIONAL AMPLIFIER APPROACH

The simplest solution for all of this is to use an operational amplifier as the input element. The generalized inverting operational amplifier configuration

is shown in figure 22. The net voltage gain here, assuming the amplifier gain A is very large, is given by:

$$\frac{e_o}{e_i} = \frac{Z_f}{Z_i}$$



$$\text{Gain} = \frac{e_o}{e_i} = -\frac{Z_f}{Z_i}\,\frac{1}{1-\frac{1}{A\beta}}\ ; \quad \beta = \text{Feedback Ratio}$$

Figure 22. Generalized Inverting Operational Amplifier Configuration

where Z_i and Z_f are the input and feedback impedances, respectively. Their junction at the amplifier input terminal is known as the summing point, and a property of this configuration is that the summing point junction has a very low (essentially zero) impedance to ground.

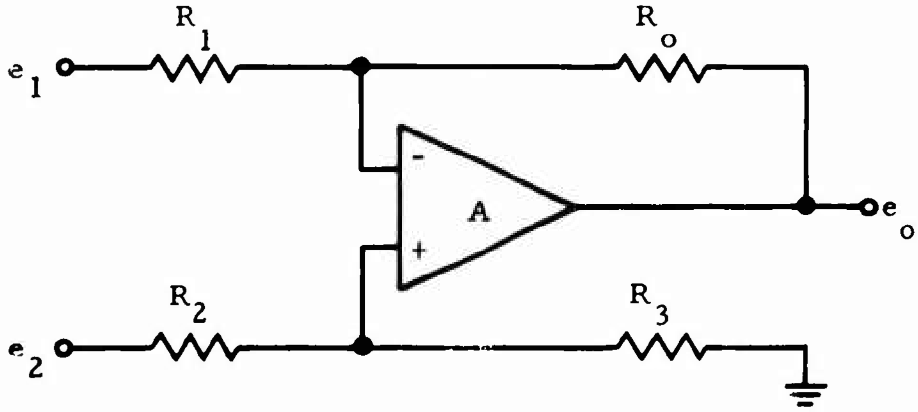
It is clear that if Z_i is taken as the capacitance existing between the pattern plate and the pickoff quadrant, the latter and its associated wiring will be connected directly to the summing point, and be at a low impedance level. This then eliminates the problems of stray pickup and shielding mentioned above. It may also be shown that any stray capacitance between the summing point and ground enters into the gain only as a second order effect, and thus the problem of the stray capacitance (C_3) directly influencing the gain in the simple follower (see figure 20) is also removed.

The use of a capacitance as the input element in this operational amplifier circuit results in a differentiation of the input signal. For sinusoidal inputs, this means a 90-degree phase shift and an amplitude response characteristic which increases directly with frequency at 20 db/decade. Such a response

emphasizes high frequency noise in the input signals and may also result in instabilities. The usual solution here is to select the feedback element (Z_f) so that it and the natural high frequency roll-off of the amplifier limit the response of the system above the designed operating frequency.

The operational amplifier configuration also has a very low output impedance (on the order of tens of ohms or less) and thus the last requirement of the input stage, matching the signal to an impedance level suitable for further processing, is also fulfilled.

The signal processing desired is simply the subtraction of the signal from one plate from the equal and opposite signal on a diagonally opposed plate. This, effectively, would double the output voltage. This is again most easily accomplished using the operational amplifier configuration shown in figure 23. The output signal is dependent only upon the ratio of resistors, and by their appropriate choice, the subtraction ratio of unity may be assured. No other active elements are required for the electronics, since the subtractor operational amplifier also has a low output impedance.



$$e_o = \frac{R_3}{R_1}\left(\frac{R_1 + R_o}{R_2 + R_3}\right) e_2 - \frac{R_o}{R_1} e_1$$

Figure 23. Generalized Operational Amplifier Circuit for Subtraction of Two Signals

Since there are four pickoff plates and the information processing consists of subtracting signals from opposite pairs, the total electronics package must consist of four input amplifiers and two subtractors. It is most convenient to split this requirement into two identical halves, each half processing a pair of plates. Breakdown of the package in this way also simplifies construction.

The final design configuration of each half of the package is shown in figure 24. The area within the dotted rectangle in the figure shows the circuitry actually contained within the amplifier package.

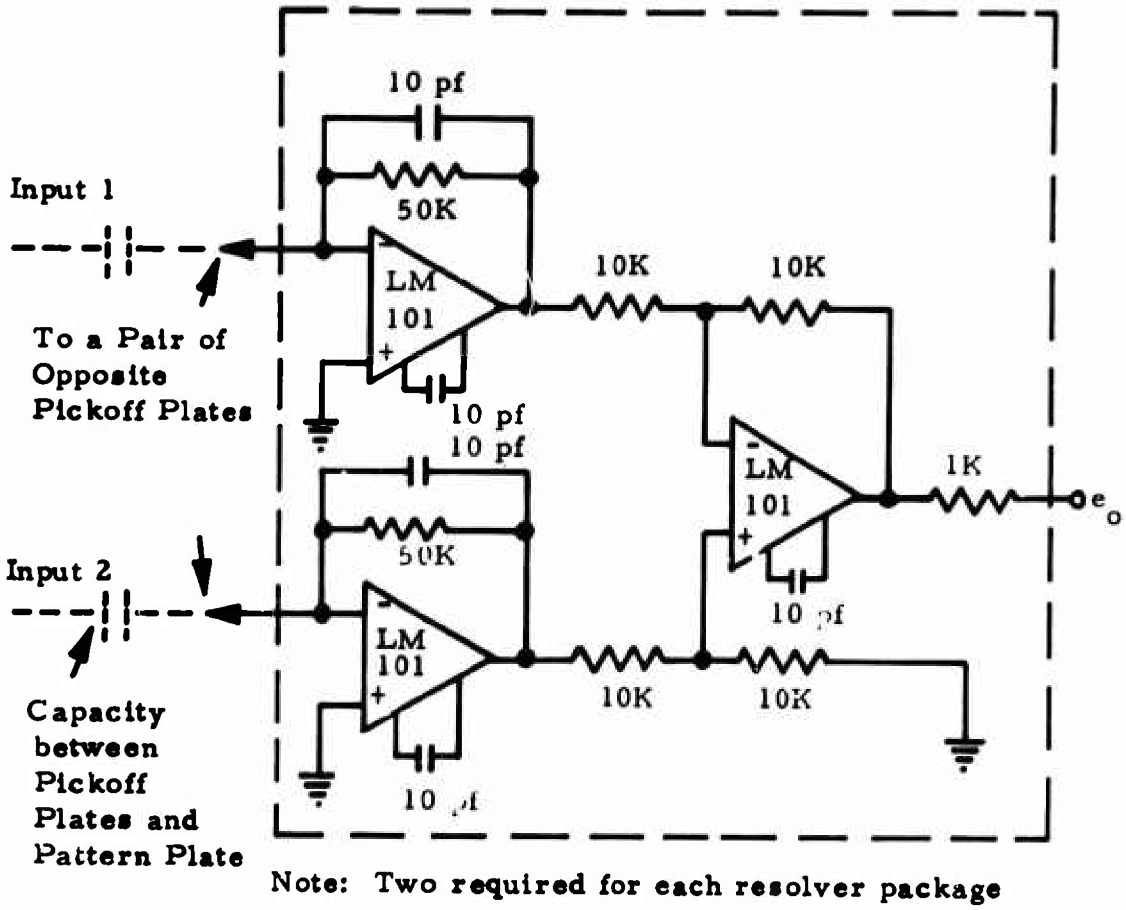


Figure 24. Final Design Configuration for Resolver Electronics Package

7.5 MECHANICAL PACKAGING REQUIREMENTS

Both the electrode system and the electronics for the capacitive resolver must fit into a space shaped like a thin disc, 0.9 inches in diameter, having a 0.375-inch hole concentric with the outer diameter. The package thickness cannot exceed 0.13 inches. Both the pattern and pickoff discs are 0.030 inches in thickness, therefore, the electronics package must be accommodated by the remaining 0.070 inches.

A hybrid microcircuit is a good way of realizing the electronics in such a severely limited package. It would be quite possible to fabricate the electronics on two chips in a fully integrated monolithic circuit, but this approach is far too costly to use on a program at this level of effort. The hybrid

technique gives more flexibility and economy at this stage. Design changes may easily be made and improvements in components can more readily be incorporated by using the hybrid technique.

7.5.1 Integrated Circuit Amplifiers

The first consideration is the operational amplifiers. All of the commercially packaged units, both in cans and various types of flat packs, are either too thick, or occupy too much of the available surface area. Thus uncased chips must be used. In general, these are 0.050 inches or less square and about 0.010 inches thick.

Next to be considered is the required operational amplifier frequency compensation. To make an operational amplifier stable in use, it is required that its gain fall off with increasing frequency in a controlled manner, usually at the 20 db/decade rate. This is accomplished with one or deliberately introduced RC low-pass filters somewhere in the circuitry. The capacitors must be supplied in the form of discrete elements external to the chip. In some cases, large values of capacitance (in the order of 0.1 to 0.01 μf) must be used. A criterion for selection, therefore, is a chip which requires the least amount of external capacitance for satisfactory frequency compensation.

At the time of this design (summer 1968) the best choice was National Semiconductor Corporation's LM101, which can be compensated satisfactorily with a single capacitor in the range of 3 to 30 pf, depending upon the usage. Three such chips are thus used in each hybrid circuit.

7.5.2 Substrates

The choice of a substrate material is influenced by the size of the production run and the level of finality of the design. Ceramics, the most common material for this application, are avoided here because of both high tooling costs and the need for design flexibility. The simplest approach utilizes an etched circuit board of 10-mil thickness epoxy fiberglass. Both sides may be used for the circuitry, simplifying the layout. Components may be attached easily by either adhesives or soldering. Electrical connections to the board can also be made by soldering. Fast access to Litton's in-house printed circuit facility encourages this approach.

7.5.3 Components: Resistors and Capacitors

Both resistors and capacitors are available from various vendors in a microminiature package for use in hybrids. The decision was made to use commercial capacitors where needed, and to construct the necessary resistors as a matched set by thin-film techniques on a secondary substrate.

One reason for this is that the final electronic performance is relatively independent of exact resistor values but is more critically dependent upon their match. This is a useful characteristic of thin film sets. Also, the exact values of the capacitors will affect circuit performance critically, and it is very desirable to be able to change capacitors as needed. This is most easily accomplished with lead-mounted discrete devices.

7.6 FINAL CIRCUIT DESIGN

7.6.1 Input Stage

The exact gain expression for the general inverting operational amplifier configuration shown in figure 22 is given by:

$$G = -\frac{Z_f}{Z_i} \cdot \left(\frac{1}{1 - \frac{1}{A\beta}}\right)$$

The operational amplifier is being used here at frequencies where its gain is not very large compared to unity; thus the exact equation must be used.

Specializing to this circuitry, refer to the schematic of figure 25 in which C_1 is the pattern to pickoff capacitance, R the feedback resistor, and C_2 a feedback capacitor to stop the differentiator and ensure a stable system. Using transform notation, then:

$$Z_i = \frac{1}{SC_1}, \; Z_f = R \parallel \frac{1}{SC_2}$$

and

$$\frac{Z_f}{Z_i} = \frac{SRC_1}{SRC_2 + 1}$$

The RC products here are made up of terms of the order of 10 pf and 50K, or 5×10^{-7} seconds and, therefore, for convenience in this discussion, the RC factors will be scaled up by multiplying them by 10^7, and the frequencies scaled down by 10^{-7}. Thus, 1 Mhz = 6.28×10^6 rad/sec = 0.628 (scaled).

The amplifier gain, A, is given on the National Semiconductor Corporation data sheet[2] for the LM101 (see figure 26) as a plot of the magnitude of gain vs. frequency, with a d-c value of about 105 db, a simple pole at around 10 hz and decreasing at 20 db/decade until it passes through unity around

[2] National Semiconductor Corporation, "LM101 Operational Amplifier Data Sheet," Santa Clara, California, 1968.

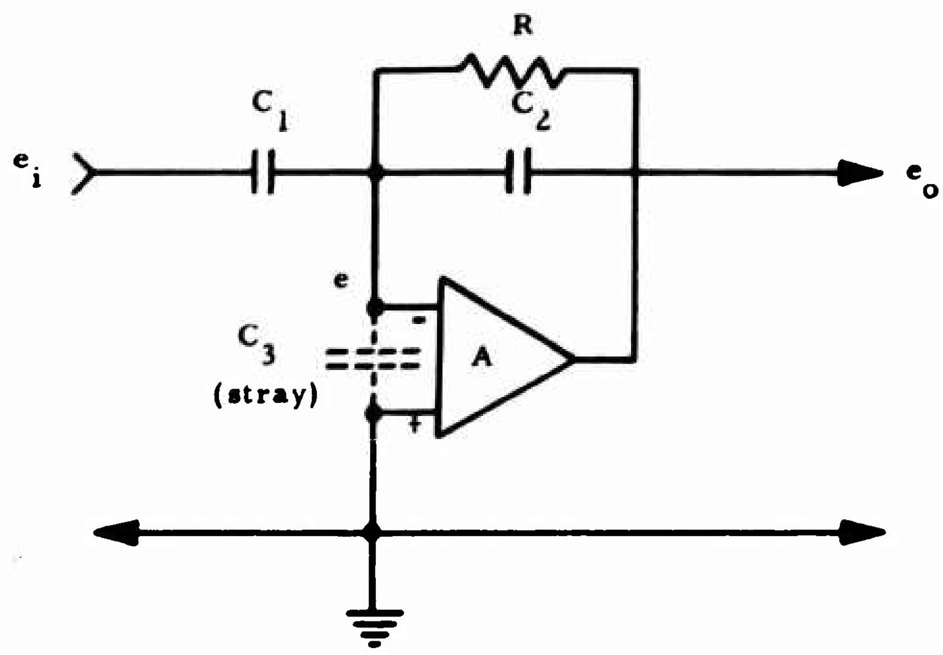


Figure 25. Operational Amplifier Network for Input Stage

1.5 Mhz ($\omega = 1$). At around 2 or 3 Mhz ($\omega = 2$), the slope decreases at a faster rate, indicating another pole and an increase of slope to 40 db/decade. The exact value of gain depends upon the capacitor that is used. Here a value of 10 pf is a good compromise between stability and high gain. The gain may be written as:

$$A(S) = \frac{K}{S\left(\frac{S}{2} + 1\right)}$$

and K may be evaluated by noting that for $S \ll 1$, $A(S)$ reduces to K/S and, picking a small ω from the data sheet

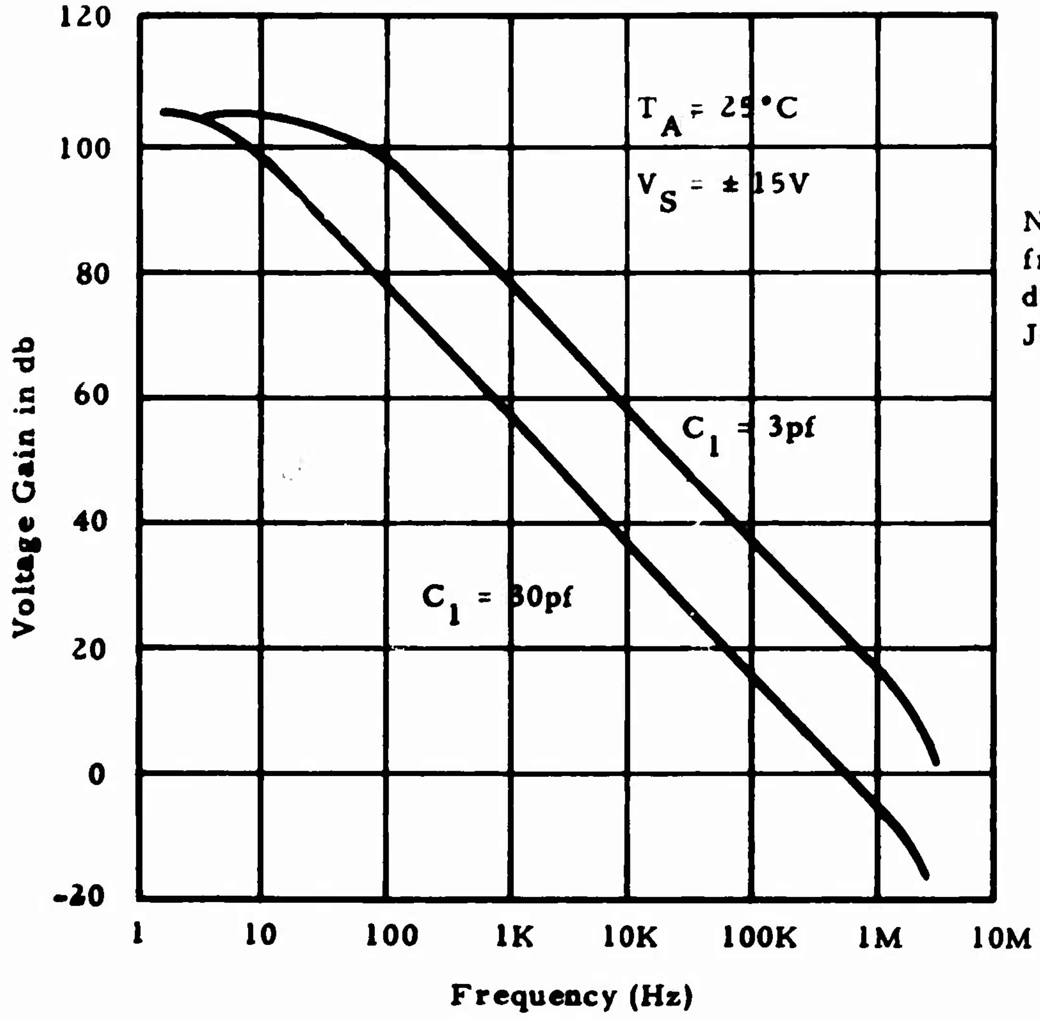
$$\omega = 2\pi \cdot 10 \text{ Khz} = 0.00628$$

and

$$A(0.00628) \cong 42 \text{ db} = 180$$

so that

$$K = (0.00628)(180) \simeq 1$$



NOTE: Data are from manufacturer's data sheet of January 1968.

Figure 26. Open Loop Frequency Response of Typical LM101 Operational Amplifier

The feedback ratio, β, may be evaluated with the aid of figure 27, which shows that it is the transfer ratio of a simple voltage divider. Note that here is included about 4 pf of stray capacitance at the operational amplifier input. The resistive component of the input impedance is neglected since the data sheet gives a minimum value of 300K and a typical value of 800K. This yields:

$$\beta = \frac{SRC_2 + 1}{SRC_t + 1} = \frac{5\,S + 1}{11S + 1}$$

where

$$C_t = C_1 + C_2 + C_3$$

and therefore

$$A\beta = \frac{1}{S\left(\frac{S}{2} + 1\right)} \times \frac{5\,S + 1}{11S + 1}$$

How stable is a system using this value of A? The two criteria for stability are; (1) that the gain margin be less than 1 and, (2) that the phase margin be at least 45 degrees. This is a second order system, which always has a gain margin less than 1, and the phase margin may be evaluated by determining the total phase shift when $A\beta$ equals unity. For this, $s \cong 0.5$ and the phase at unity gain $\cong$ 120 degrees. Thus the phase margin is $180^\circ - 120^\circ$ (or 60°) which is adequate.

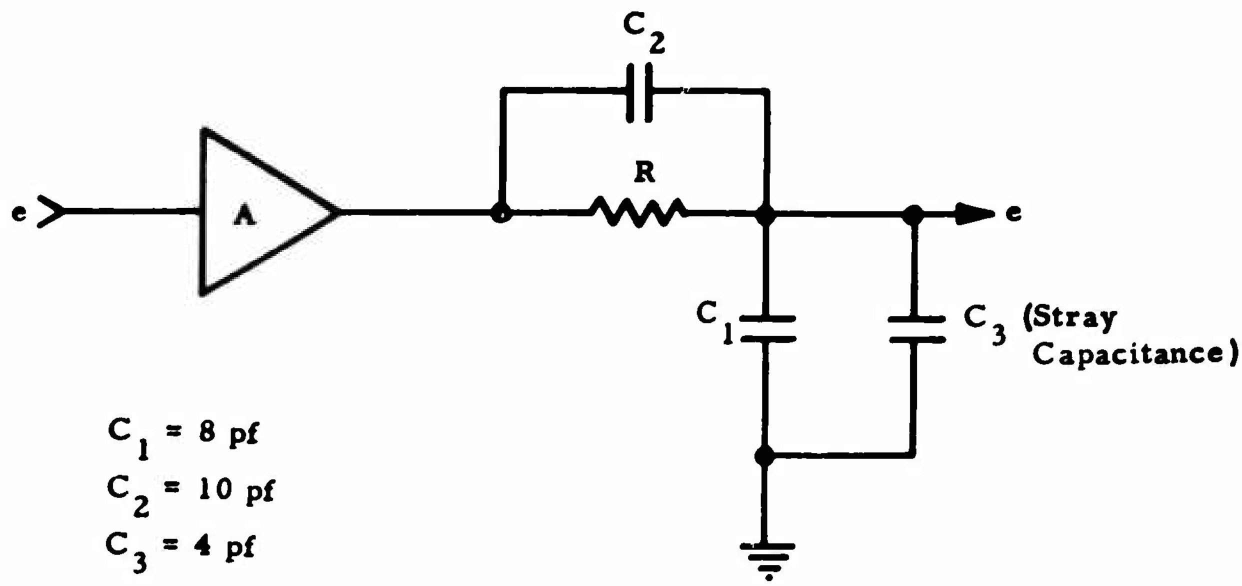


Figure 27. Schematic for Computing β, the Input Feedback Ratio

The closed-loop gain expression may now be evaluated as

$$G(S) = -\frac{4S}{5S+1} \cdot \frac{1}{1 + \frac{S(11S+1)}{5S+1}} = -\frac{4S}{11S^2 + 6S + 1}$$

where the factor $1/S_2 + 1$ in A(s) has been dropped for computational convenience, as this pole is considerably above the frequencies of interest.

The asymptotic behavior may quickly be found.

$$S \ll 1, \; G \longrightarrow -4S$$

$$S \gg 1, \; G \longrightarrow -\frac{4}{11S} = -\frac{0.364}{11S}$$

For numerical evaluation, let $S = j\omega$, and obtain

$$G = \frac{-j4\omega}{\left(1 - 11\omega^2\right) + j6\omega}$$

and

$$|G|^2 = \frac{(4\omega)^2}{\left(1 - 11\omega^2\right)^2 + (6\omega)^2}$$

$$\phi = -90^\circ - \tan^{-1} \frac{6\omega}{1 - 11\omega^2}$$

The gain magnitude and phase have been plotted in figures 28 and 29, respectively, along with the experimentally measured gain and phase.

7.6.2 Second Stage

The operational amplifier subtractor is shown in figure 23 together with the appropriate functional equation:

$$e_o = \frac{R_3}{R_1}\left(\frac{R_1 + R_o}{R_2 + R_3}\right) e_2 - \frac{R_o}{R_1} e_1$$

For a linear subtraction of e_1 and e_2, the following obviously is required

$$\frac{R_3}{R_1} \frac{R_1 + R_o}{R_2 + R_3} = \frac{R_o}{R_1}$$

Let $R_o/R_1 = 1$, and then arrive at a relationship between R_2 and R_3:

$$\frac{R_3 + R_2}{R_3} = 2$$

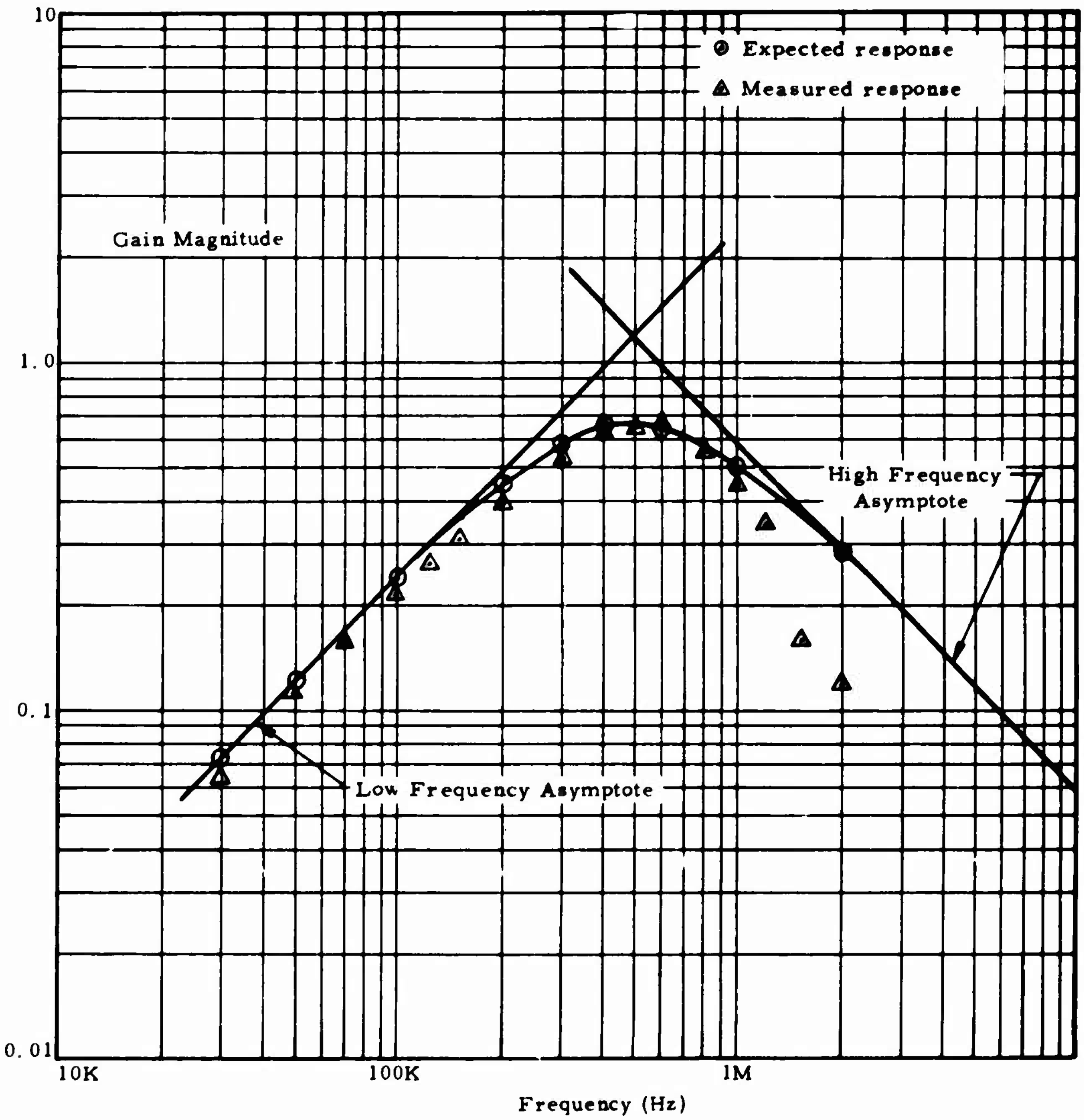


Figure 28. Capacitive Resolver Electronics Gain Characteristics of Input Stage

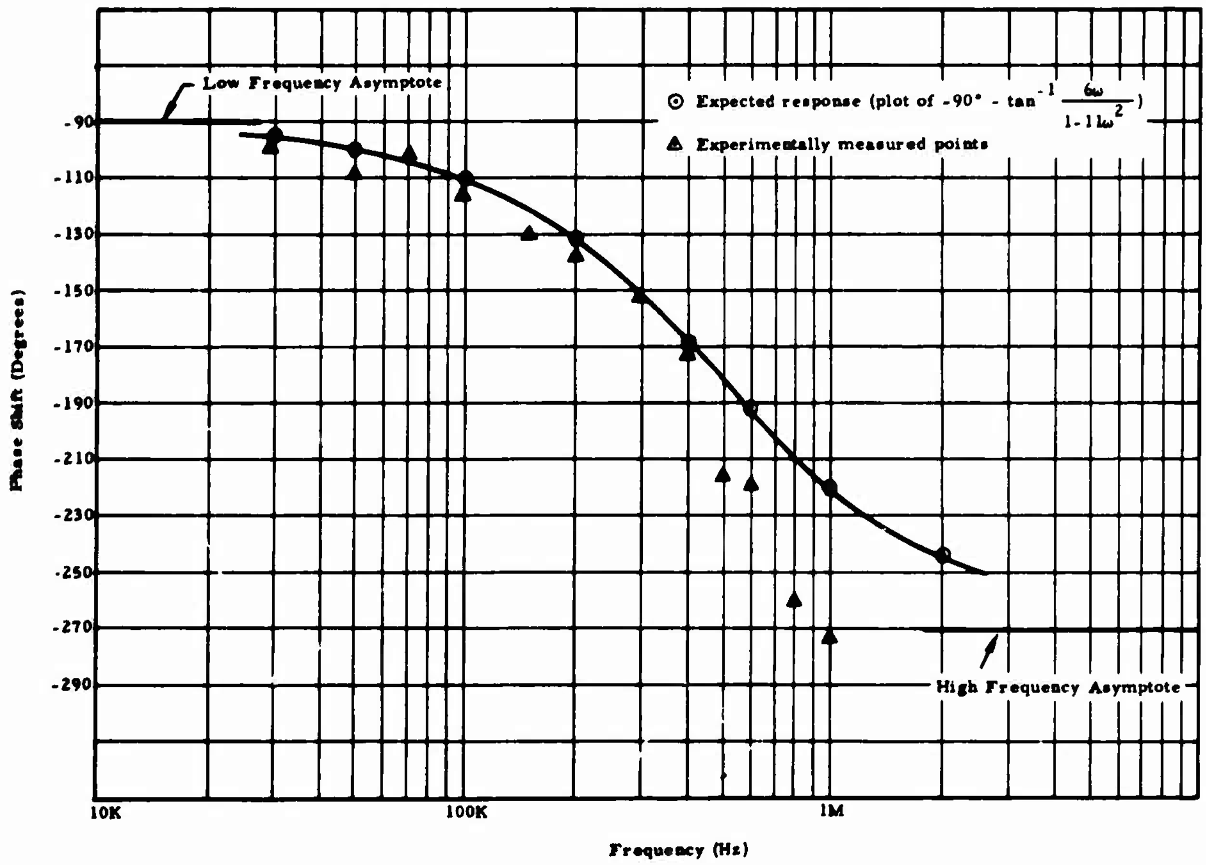


Figure 29. Capacitive Resolver Electronics - Phase Characteristics of Input Stage

This may be determined by noting that it is good practice for each input of an operational amplifier to see approximately the same d-c resistance; thus the first order effect of offset currents is cancelled. This requirement is then

$$R_1 \,||\, R_o = R_2' \,||\, R_3$$

which gives the condition that all four resistors must be equal.

A numerical value of 10K is a good choice. It is small compared to amplifier input impedances and various stray reactances at 100 Khz, and is large enough so that the network will not load the amplifier or result in exessive power dissipation.

For this second stage then:

$$A(S) = \frac{1}{S}; \frac{Z_f}{Z_i} = 1; \beta(S) = \frac{1}{2}$$

and

$$G(S) = 1 \cdot \frac{1}{1 + \frac{1}{1/2S}} = \frac{1}{1 + 2S}$$

This stage has a net voltage gain from either input to the output of unity, thus its frequency response will be flat in amplitude from zero to a corner at $\omega = 0.5$ or $f = 0.8$ Mhz. The phase shift would vary as $\tan^{-1} 2\omega$ and hence is a small number for operating frequencies much less than 0.8 Mhz.

7.6.3 Complete Amplifier

The gain expression for the complete amplifier is simply the product of the gains of its separate stages:

$$G(S)_{\text{total}} = \frac{4S}{\left(11S^2 + 6S + 1\right)(1 + 2S)}$$

The low-frequency asymptote is the same as for the preamplifier,

$$\lim_{S \to \infty} G(S) = 4S$$

and the high frequency response will fall off at 40 db/decade because of the second stage roll-off:

$$\lim_{S \to \infty} G(S) = \frac{4S}{22S^3} = \frac{2}{11S^2}$$

Figure 30 shows these asymptotes and measured response curves.

The net phase shift of the complete amplifier is simply:

$$\text{Arg } G_{\text{total}}(S) = \text{Arg } G_{\text{preamp}} + \text{Arg } G_{\text{subtractor}}$$

or

$$\phi = -90^\circ - \tan^{-1} \frac{6\omega}{1 - 11\omega^2} - \tan^{-1} 2\omega$$

This is given in figure 31 for the non-inverting input; the other input would introduce an additional factor of 180 degrees.

7.6.4 Output Protection

The electronics on the LM101 chip is designed to limit the output current to a safe value in case of accidental short-circuit of the output. The resultant output current causes a power dissipation in the chip which is quite safe if the chip is bonded to the usual metal header or other appropriately heatsinked package. Litton's use of this chip does not provide adequate heatsinking for the short circuit case and, therefore, to protect the chip, it is advisable to add a current limited impedance to the output

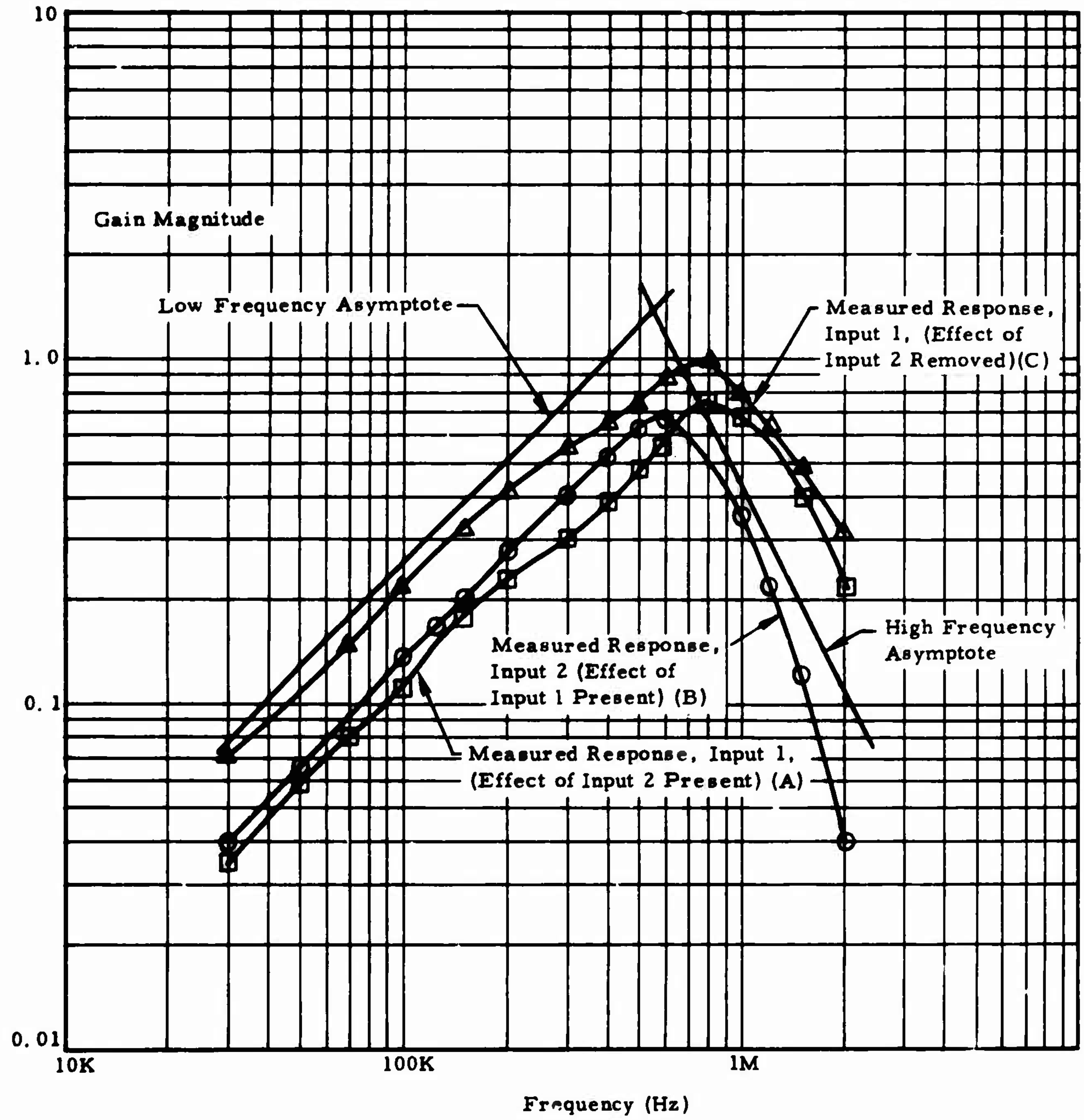


Figure 30. Capacitive Resolver Electronics - Gain Characteristics of Entire Amplifier

signal path. A value of 1K will limit the current to a few milliamperes at a few volts output, and this value will not increase the output impedance to an excessive value. Two feet of coaxial cable at 30 pf/foot, has a reactance of 30K at 100 Khz. This is large compared to 1K.

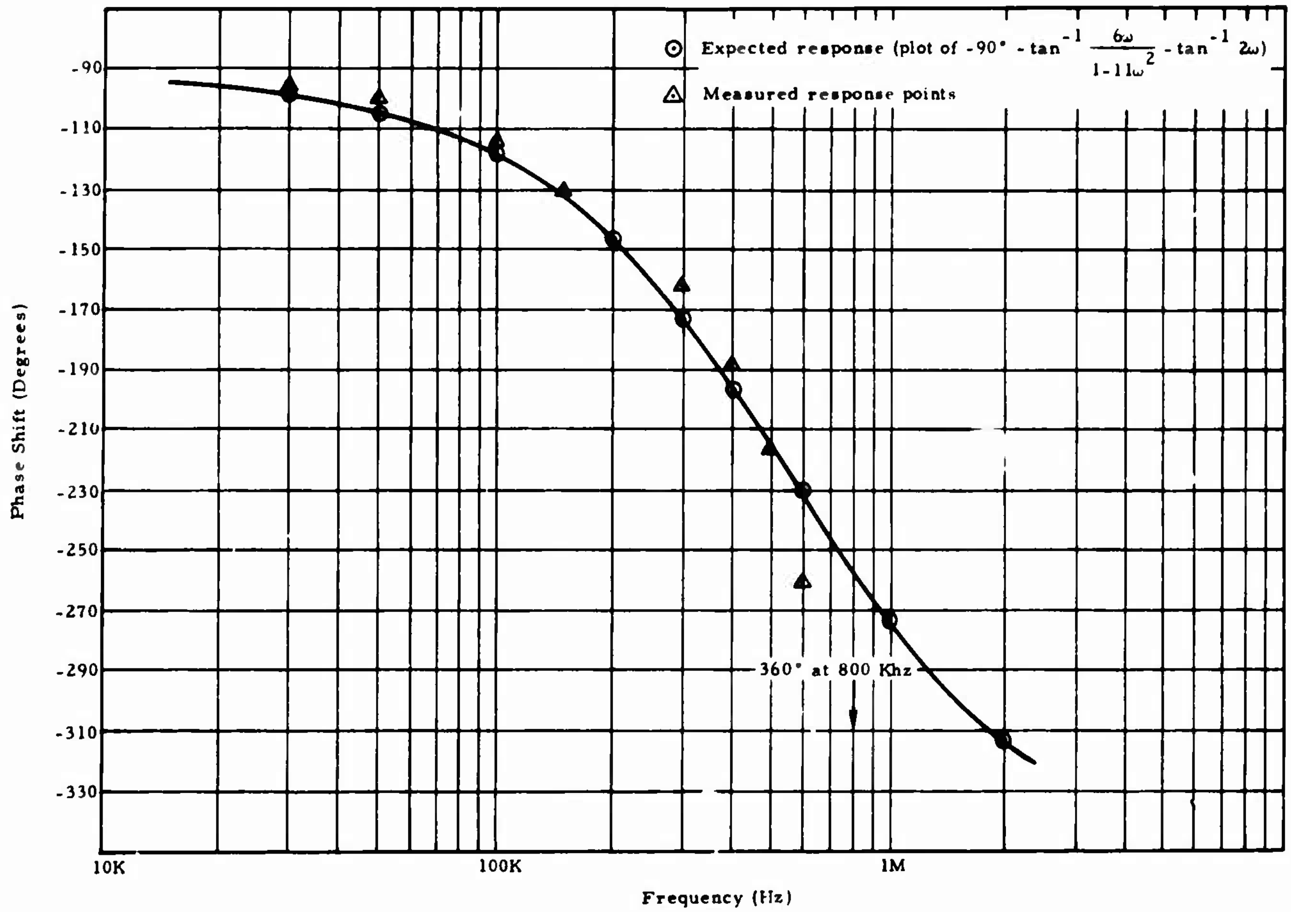


Figure 31. Capacitive Resolver Electronics - Phase Response Complete

SECTION VIII

ELECTRONICS FABRICATION AND PERFORMANCE

8.1 SCOPE

In this section, the assembly of the hybrid electronics package is outlined, together with the electrical test setup for the amplifiers. The electrical performance of a typical amplifier unit is presented and compared with the predicted characteristics.

8.2 FABRICATION AND PROCUREMENT OF COMPONENTS

The electronics for the miniature capacitive resolver consist of two hybrid microcircuit channels which are mounted to the back of the metallized quartz pickoff substrate. Both channels are identical and each consists of the following parts:

- One printed circuit card
- Five Scionics 10-pf pellet capacitors
- One thin film resistor network
- Three LM101 operational amplifiers

8.3 ELECTRONICS ASSEMBLY

The backs of the printed circuit cards are coated with epoxy and cured in an oven. This is done to provide electrical insulation below the circuit cards. Next, the five capacitors are installed using a minimum of solder. This step is critical as solder on the tops of the capacitor leads makes it difficult to bond leads to them ultrasonically. A thin coat of epoxy is then applied to the resistor substrate and it is positioned on the circuit card. Next, the three operational amplifiers are installed using a silver-filled, conductive epoxy. The epoxies are oven cured. Care must be taken to keep the surfaces of the amplifiers and resistor substrate parallel to the circuit board surface. The parallel surfaces are important in the ultrasonic bonding operation. One mil aluminum wire is bonded ultrasonically from the amplifiers and resistor substrate to the gold-plated copper pads on the printed circuit cards (see figure 32). These electronic assemblies are then tested.

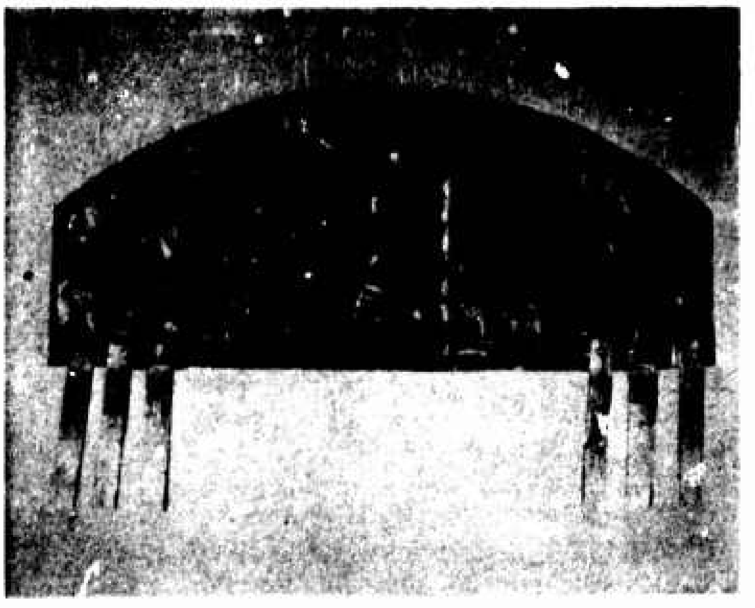


Figure 32. Completed Electronic Assembly for One Channel Prior to Encapsulation

After testing, the components are encapsulated with polyurethane resin by dipping and heat curing; four coats are usually applied. After the final cure, the circuits are again tested, and if satisfactory are now ready for assembly onto the pickoff substrate (see figure 33).

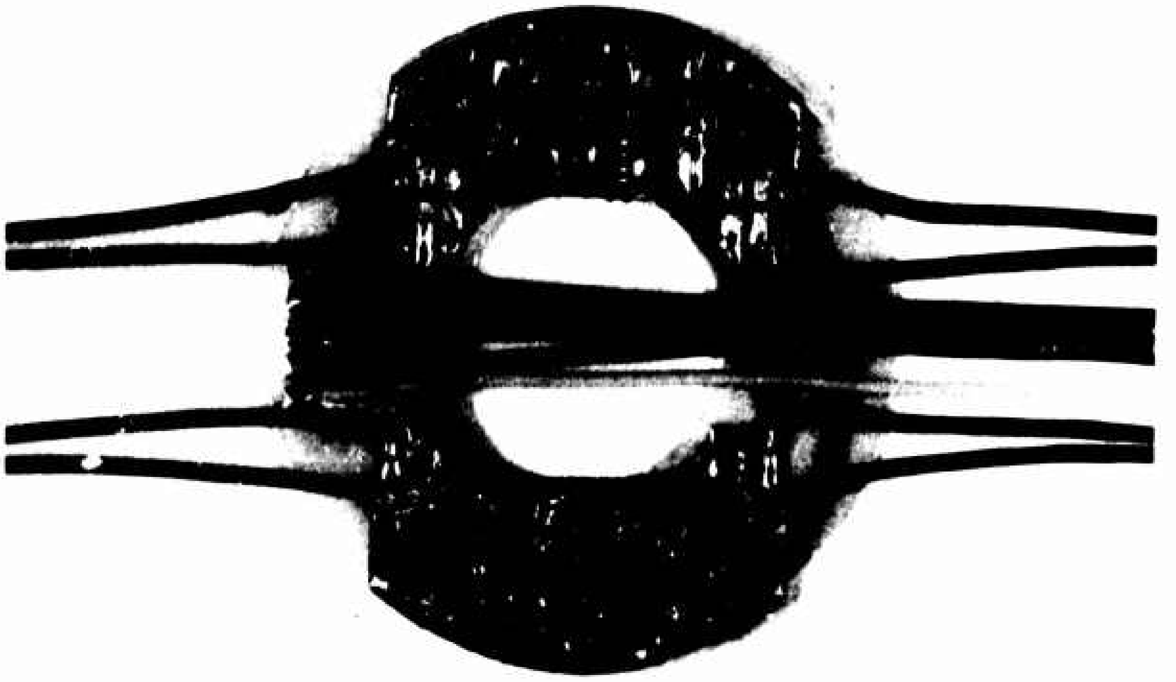


Figure 33. Complete Electronic Assembly

8.4 ELECTRONICS TEST

A block diagram of the electronics test setup is shown in figure 34. It has been designed for two types of tests: (1) A quick go/no-go test to indicate general amplifier performance and, (2) complete frequency and phase response measurements.

The amplifier etched circuit board is temporarily fastened to a carrier for convenience in handling during fabrication and test. The carrier is a two-inch square piece of circuit board, having an array of conductors which are temporarily connected to the hybrid's terminal connections. The conductors on the carrier board terminate on its edge, and electrical connection is made through a conventional female card connector into which the carrier may be plugged.

A-c signals for the tests are provided by a Hewlett-Packard 650 A sine wave generator, which covers the desired frequency range and delivers its signals to three places: (1) the oscilloscope sweep trigger input, (2) the reference channel on the oscilloscope input, and (3) the test fixture input.

Certain precautions must be observed in the checkout of operational amplifier circuits. Inputs and outputs may not be arbitrarily open or short circuited, as this may upset feedback loops upon which proper operation depends. Here, the input signals must be applied through a proper source impedance, and the unused inputs must also be grounded through an appropriate impedance. A switch is provided so that a rapid check of each input is possible. Frequency response tests are made with a small capacitor to duplicate the design conditions of section VII and, for general tests, a resistive impedance is used.

Both amplitude and phase measurements are performed using the oscilloscope, which provides sufficient accuracy for this work. Phase is measured by noting relative displacements of the two displayed sine waves. Lissajous pattern methods with an XY oscilloscope are available, if required. The go/no-go tests involve noting approximate output amplitudes and the presence of a 180-degree phase shift between the A and B inputs at a fixed 100 Khz frequency.

For trouble analysis and internal diagnostic measurements, it is desirable to make electrical connections to locations on the hybrid circuit board or on the operational amplifier chips. To facilitate this, the carrier board is attached to a microscope stage fitted with adjustable probes to contact the circuitry as desired.

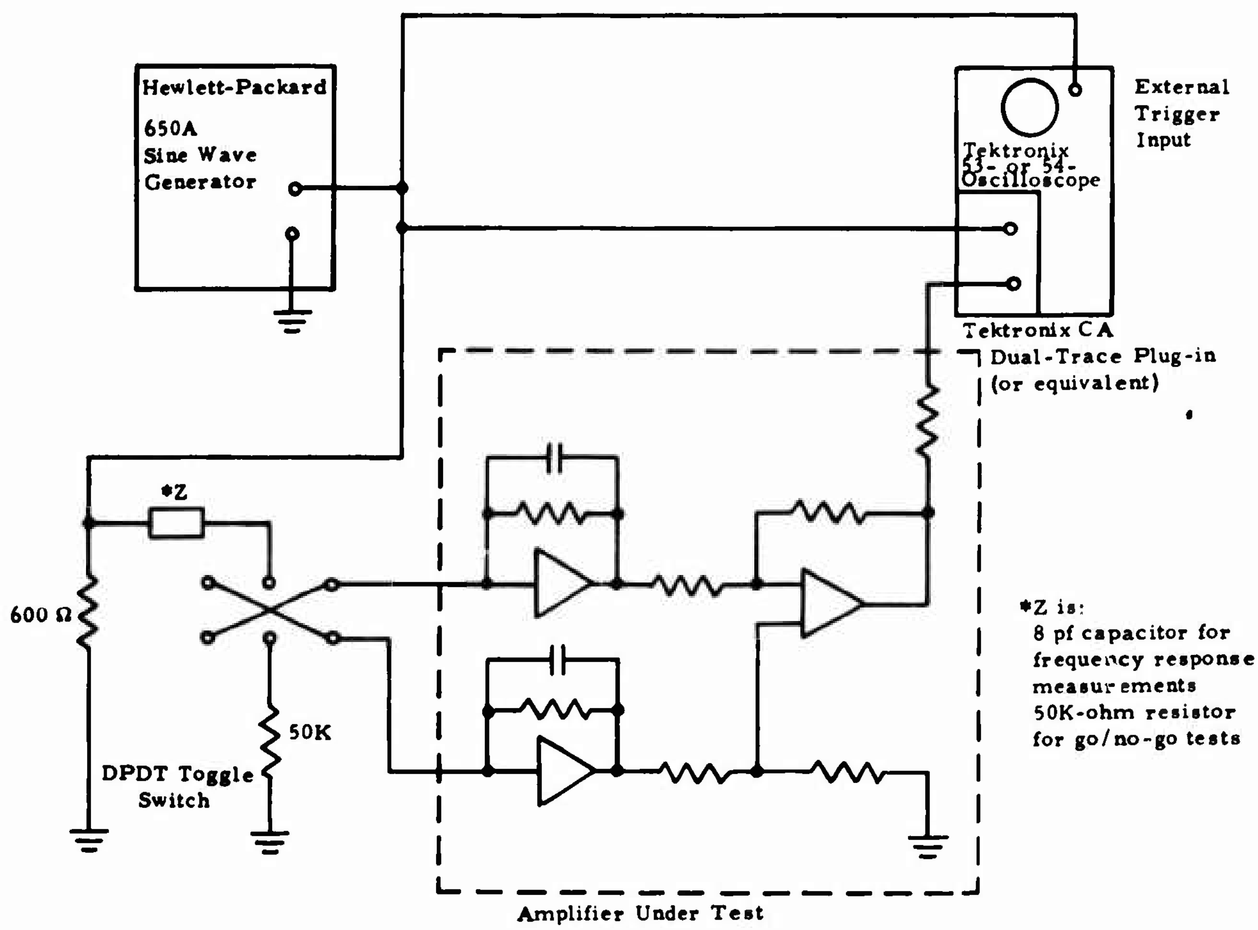


Figure 34. Electronic Test Setup for Amplifier Checkout

8.5 ELECTRICAL PERFORMANCE

8.5.1 Summary of Amplifier Performance

Table IV summarizes the measured performance of one of the complete amplifier sets.

TABLE IV. SUMMARY OF AMPLIFIER PERFORMANCE

Characteristic	Parameter
Voltage gain from either input to output, using 8 pf input capacitor at 100 Khz	0.22
Phase shift from inputs to output at 100 Khz	115° and 290°
Power supply drain (no difference between zero and 1-volt signal input)	+15 supply 6 ma; -15 supply 15 ma
Residual noise output (inputs terminated in 8 pf and 50K, respectively)	10 mv peak-to-peak, observed on oscilloscope
Harmonic distortion	0.9% total at 0.4 volts rms input (0.45%, 2nd; 0.8%, 3rd; remainder, negligible)
Linearity	better than 0.2%; zero to 1.2-volt peak input

8.5.2 Frequency and Phase Response

These measurements have already been given on the plots of their expected values, figures 28 thru 31. Although this information is not essential to this work, it furnishes a useful check on performance and can help validate the analytical study.

The gain (figure 28) and phase (figure 29) measurements of the input stage agree with the simple model. The increasing discrepancies above a megahertz (gain) or 400 Khz (phase) are caused by the second corner in the LM101 gain around 2 to 3 Mhz, which was neglected in the theoretical discussion.

The gain characteristics of the entire amplifier (figure 30) show an interesting effect, indicating the presence of overall feedback. There are two inputs to the amplifier package where a signal may be introduced, designated by 1 and 2 in figure 24.

The test setup of figure 34 is used, wherein the input under test is fed voltage through an 8-pf capacitor and the other input is grounded through a 50K resistor. This is an unsymmetrical arrangement and, unfortunately, the unused input picks up some signal through stray capacitance. This signal is then combined with the test signal in the subtractor stage. If the test signal is fed into input 1, the pickup from input 2 can be eliminated by grounding the non-inverting input connection to the subtractor stage, since this does not effect the signals entering the inverting input. If the test signal is applied to input 2, pickup cannot be eliminated through input 1, because grounding out the inverting input to the subtractor stages takes out the feedback and deranges the operation of the stage. The output or input of the no. 1 operational amplifier cannot be grounded safely, since this also removes the feedback and could result in destructive operating conditions for the amplifier chip.

Figure 30 shows the asymptotes and measured response for these three conditions. Curves A and B show the response from each input, subject to any pickup effects at the other input. Note that the low frequency gain here is consistently a factor of two less than expected. For curve C, where this pickup can be eliminated, the low frequency response is quite close to the predicted levels indicating the removal of negative feedback. Where the high frequency response is greater than predicted, positive feedback effects are indicated. A possible contributor to this is the close proximity of all the circuit resistors on one substrate; future designs could have greater separation between such components belonging to different stages to avoid possible oscillation if newer operational amplifiers with improved high frequency response are employed. These effects are not significant at 100 Khz, the design operating frequency.

8.5.3 Other Effects

It should be noted here that the peak-to-peak output signal capability of this amplifier is frequency limited because of the finite slewing rate of the operational amplifiers. For example, the input signal must be 1 volt or less at frequencies around one megahertz.

The operational amplifier chips are light sensitive, and 60-cycle pickup and other effects have been observed when the amplifier units are exposed to strong light, such as when under microscopic inspection. This can, of course, be eliminated by using an opaque encapsulant or cover for the amplifier assemblies.

SECTION IX

ENGINEERING MODEL OF 0.9-INCH CAPACITIVE RESOLVER

9.1 SCOPE

The fabrication of a 0.9-inch engineering model of the capacitive resolver consists basically of three phases:

a. Fabrication of the pattern and pickoff substrates.

b. Assembly of the electronics to the pickoff substrate.

c. Performance testing

Each of these phases is discussed in detail in this section.

9.2 FABRICATION OF PATTERN AND PICKOFF SUBSTRATES

The fabrication procedure for the engineering model substrates differs from that used for the standard pattern and pickoff study plates; the latter are 1/8-inch thick while the engineering model plates are only 0.030-inch thick. The quartz discs are ground to a thickness of about 0.050-inch and then the 0.375-inch center hole and 0.020-inch electrical feedthrough holes are drilled. The disc is then ground to its finished thickness of 0.030-inches. This two-step procedure is required because the drilling of the large center hole results in a chipping around its edges in areas which are required for metallization. Final grinding after drilling removes the chipped region and leaves a full-sized, flat surface.

Some difficulty was experienced in obtaining good adherence of the metallization to very smooth quartz surfaces; thus the discs are not polished but are left with a fine grind finish of about 10 microns roughness. The early use of a metal to fill the electrical feedthrough holes has been eliminated. Contact is now made by metal film deposition in the holes.

The hole metallization may be accomplished in two ways, the simplest of which is a chemical deposition process. The carefully cleaned disc is bathed in a stannous chloride solution, rinsed, and then immersed in a palladium chloride bath, where a monolayer of metallic palladium is deposited over the entire surface of the disc by chemical reduction from a

residual layer of stannous ions. This film is built up in thickness with chemically deposited copper and is further increased to about 0.2 mils thickness with electroplated copper. The feedthrough holes and the area of the disc for about a millimeter around them is protected with a synthetic rubber compound; then the exposed copper is chemically removed. This procedure leaves a little copper eyelet on either side of the feedthrough holes.

Metal films with better adherence properties are produced by a vacuum evaporation method using the experimental observation that nichrome films adhere more tenaciously to quartz or glass substrates than most other metals. An evaporated nichrome film is laid on all over the disc, and followed by a copper film. Again, final thickness is built up in electroplating baths, the desired areas masked, and the excess metal chemically removed.

The substrate which is to become the pattern disc is coated on one side with about 5000 Å of aluminum either by evaporation or using a sputtering process (which gives better adhesion). A nichrome underlayer, or a nichrome film itself, cannot be used here because only aluminum is suitable for use in photo-etching fine line patterns. The aluminum surface is then coated with photoresist, exposed to the appropriate pattern mask, developed, and etched, resulting in the fine line pattern which delineates the various pattern elements. The excess photoresist is removed and the disc is cleaned and checked for electrical isolation of all the pattern elements. If it is satisfactory, lead wires are soldered into the holes and the disc may be installed in the lower half of the test fixture.

There are a number of possible arrangements for combining the pickoff disc and its associated electronics. The simplest method is to deposit a circuit pattern on the rear face of the pickoff disc and attach the amplifier substrates and connections directly to the back of the disc. This circuit pattern is etched from a vacuum-deposited copper-nichrome film with processes described above. The other assembly method is to place the electronics on a thin etched circuit card which is, in turn, bonded to the back of the pickoff disc. In this case, the eyelet-style metallization on the rear of the disc is adequate, and no further processing is used. For either assembly method, the front surface of the disc is aluminized and etched to form the pickoff plate geometry in a manner identical to that used for the pattern discs.

9.3 ASSEMBLY OF ELECTRONICS TO PICKOFF SUBSTRATES

As has been mentioned, the electronics assembly may be placed either directly on the rear of the pickoff disc, or upon a separate circuit card; the same etched circuit pattern is used for either method. The use of the disc as the substrate for the electronics assembly has the advantages of compactness and reduced total height, and the disadvantage that the assembly cannot easily be taken apart without irreversible damage. In addition, the attachment of objects to the rear of the disc can cause stresses on the disc which will warp it slightly and decrease its operating precision. Attachment of all the electronics to a separate subassembly has the advantages that this

subassembly may be more easily checked and repaired, and its attachment to the rear of the disc can be accomplished in a manner which creates less warpage of the disc.

The tested amplifier pairs are cemented with a suitable adhesive to the back of the pickoff disc or to the separate circuit card. The necessary interconnects and lead wires are attached, and for ease of alignment in the test fixture, the connections to all four pickup quadrants are brought out separately, as are their corresponding amplifier inputs. This allows both mode A and mode B tests on the engineering model.

9.4 MOUNTING OF ENGINEERING MODEL ELEMENTS IN TEST FIXTURE

Mounting of the pickoff assembly into the upper half of the test fixture is performed in two ways: A very sturdy mounting technique is to fasten to the rear of the disc, in the area outside of the amplifier boards and interconnects, two mounting bars, each 3/8 inch long and about 0.060 inch square cross section. By carefully controlling the thickness of the bars, the disc surface may be maintained very parallel to the plane of the mounting fixture, thus simplifying the alignment procedures. However, this method requires the attachment of material to the disc, a possible cause of warping due to differential thermal expansion. In addition, support in this manner creates a lever arm extending across most of a diameter of the disc, and relative expansion between the disc and the support to which the bars are attached can further increase deformation of the disc.

A superior mounting method is to support the disc assembly at its center hole. A short metal stud is located on the upper half of the test fixture; its diameter is slightly larger than the center hole of the disc, and it has a shoulder machined into its lower end onto which the disc may rest. The disc is held in place with an appropriate wax. This method gives adequate support for the disc with a minimum of warpage to its surface.

The mounting of the pattern disc in the lower half of the test fixture is also somewhat critical. The method which has been found to be the most satisfactory is to support the disc over its entire rear surface on a flat, ground metal surface, in which small holes are provided for the three pattern electrical leads. The metal plate is given a very uniform thin coat of wax by painting on a solution of the wax in a suitable solvent which is then allowed to evaporate. The plate and the disc are heated to the melting point of the wax (about 140°F), placed in contact, and allowed to cool with sufficient pressure on the disc to assure a uniform contact with the plate over its rear surface. This tends to force the disc to assume the degree of flatness provided by the mounting plate, and reduces the effects of any warpage it may have when not so constrained. The guard ring surrounding the pattern is grounded to the fixture frame by a conductive paint applied on top of the fillet surrounding the disc.

Figure 35 shows the upper half of the test fixture with a mounted engineering model pickoff, and figure 36 shows the lower half with a mounted pattern.

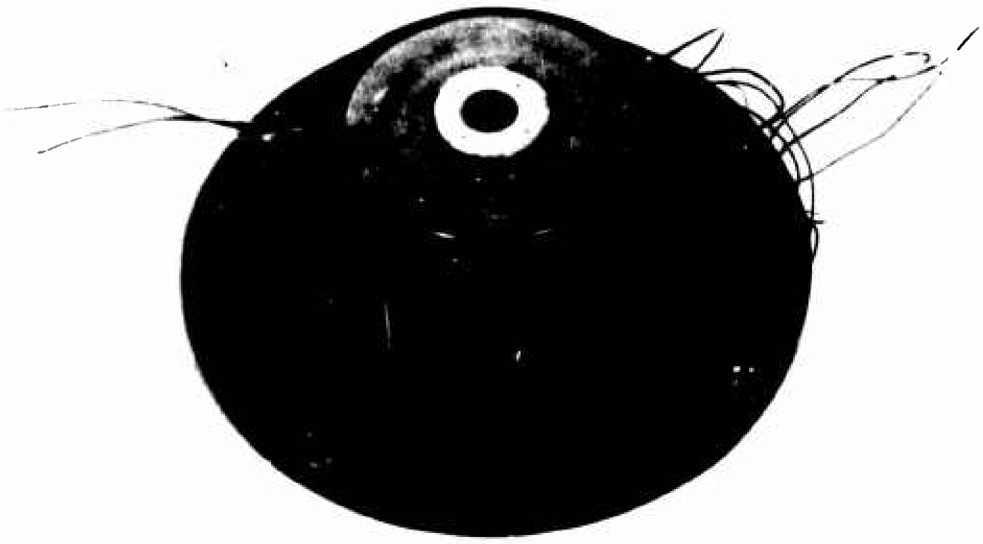


Figure 35. Engineering Model Pickoff in Upper Half of Test Fixture

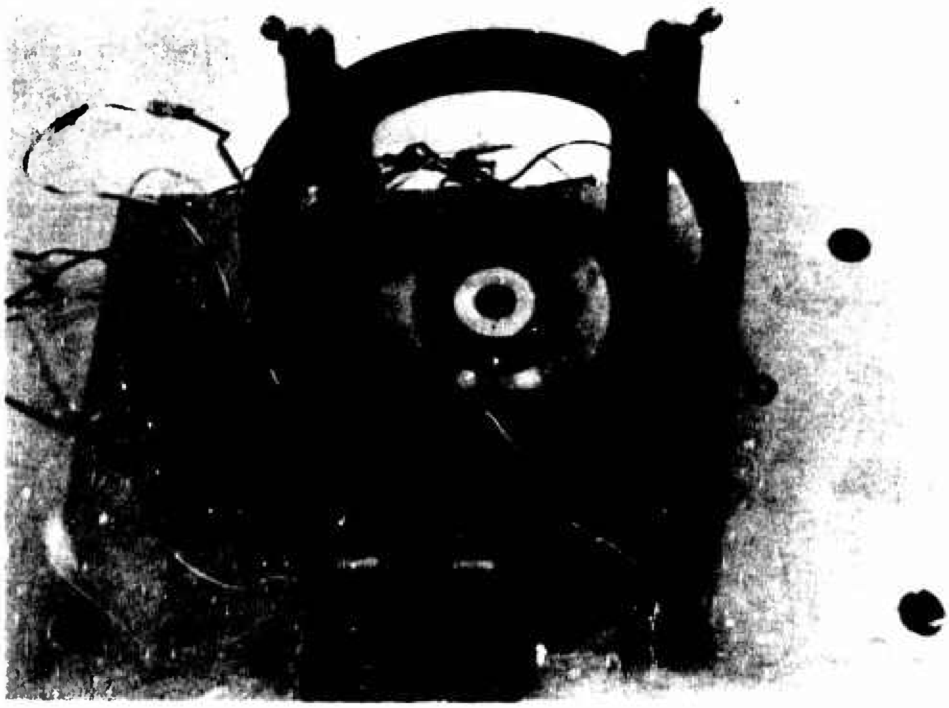


Figure 36. Engineering Model Pattern in Lower Half of Test Fixture

9.5 PERFORMANCE TEST

There are three important areas where the engineering models differ from standard pattern and pickoff test plates, and which will effect performance.

a. The on-board electronics assemblies, as compared with the off-board, or external amplifiers.

b. Guard ring requirements. The small substrate diameter here now means that there is only 0.025 inches radius left for a guard ring outside the actual pattern or pickoff metallization.

c. The 0.030 inch thick discs are 1/4 as thick as the test plates. In general, the deflection of the thinner discs under similar loading to the thick plates would be 4^3, or 64 times as much, and possible deformation due to mounting must be considered.

An extensive series of tests was made to evaluate these considerations, using various engineering models of the patterns and pickoffs, tested against each other and against the standard patterns and pickoffs. The gross results are:

a. Guard rings are definitely required for satisfactory performance and the 0.025-inch space available is sufficient.

b. The on-board hybrid electronics perform as satisfactorily as the external discrete breadboard electronics.

c. The deformation of the plates by any mounting method used must be less than about 0.1 mil (deviation from a plane surface) if the desired accuracy is to be obtained.

Detailed measurements on the engineering model elements are shown in table V, and the data reduction printouts from DFCAP4 for these cases are presented in figures 37 thru 39. The design goal of a 10-arc-minute device has been met.

TABLE V. PERFORMANCE TESTS OF 0.9-INCH DIAMETER ENGINEERING MODEL CAPACITIVE RESOLVER ELEMENTS

Run and Date	Pattern Used	Pickoff Used	Gap (Mils)	Error (Arc Minutes)	*Electronics Used
1B 4-8-69	Standard	EM 2	3.0	10.2	On-board
1B 4-17-69	EM 3	Standard	3.0	10.2	External
1B 4-17-69	EM 3	EM 2	3.0	10.2	On-board

*Opposite plates summed electronically in all cases.

NOTES

1. Both standard and engineering model (EM) pattern/pickoff substrates have 0.020-inch diameter holes metallized for feedthroughs.

TABLE V. PERFORMANCE TESTS OF 0.9-INCH DIAMETER ENGINEERING MODEL CAPACITIVE RESOLVER ELEMENTS (cont)

2. Surface runout (maximum excursion from plane surface)		
	Standard pattern:	0.04 mils
	EM 2 pickoff:	0.15 to 0.20 mils
	EM 3 pattern:	0.05 mils

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B130 040869	0.9SPH/EM2Q	9.490E-04	4.087E-04	5	5	12301
1B230 040869	0.9SPH/EM2Q	1.265E-03	4.593E-04	5	5	12302
1B130 040869	0.9SPH/EM2Q	9.490E-04	4.087E-04	5	5	12301
1B230 040869	0.9SPH/EM2Q	1.265E-03	4.593E-04	5	5	12302

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.002673	0.0	-0.009760	0.0	0.002673	0.0	0.009760	0.0
2	0.338799	0.940859	0.940450	-0.339932	-0.338799	-0.940859	-0.940450	0.339932
3	-0.002954	-0.008886	-0.008036	0.002609	0.002954	0.008886	0.008036	-0.002609
4	-0.000307	0.000019	0.000389	0.000608	0.000307	-0.000019	-0.000389	-0.000608
5	-0.000113	-0.000235	0.000186	-0.000160	0.000113	0.000235	-0.000186	0.000160

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-70.20 DEGREES	-70.13 DEGREES	-70.20 DEGREES	-70.13 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -70.16 DEGREES, DIFFERENCE IN ANGLES = 3.451E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.005345	0.0	0.019520	0.0
2	1.999999	0.001206	0.001202	1.999999
3	-0.006800	0.017451	-0.015702	-0.006245
4	0.000510	-0.000345	0.001288	0.000654
5	0.000419	-0.000309	-0.000383	-0.000307

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 10.24 ARC MINUTES AT 0.0 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000008	0.0
2	0.001472	-0.000579
3	0.001009	0.000280
4	0.000425	0.000161
5	0.000239	0.000031

Figure 37. Test Data Summary - 0.9-Inch Engineering Model Pickoff Against Standard Pattern

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	N	CODE
1B130 041769	0.9STO/EM3P	7.896E-04	3.127E-04	5	5	12301
1B230 041769	0.9STO/EM3P	8.036E-04	3.127E-04	6	5	12302
1B130 041769	0.9STO/EM3P	7.896E-04	3.127E-04	5	5	12301
1B230 041769	0.9STO/EM3P	8.036E-04	3.127E-04	6	5	12302

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.006686	0.0	-0.003721	0.0	0.006686	0.0	0.003721	0.0
2	0.743697	0.668517	0.667451	-0.744654	-0.743697	-0.668517	-0.667451	0.744654
3	-0.004726	-0.007862	-0.007704	0.004922	0.004726	0.007862	0.007704	-0.004922
4	-0.001081	0.000596	-0.001093	0.000183	0.001081	-0.000596	0.001093	-0.000183
5	0.000007	-0.000291	-0.000144	0.000450	-0.000007	0.000291	0.000144	-0.000450

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-41.95 DEGREES	-41.87 DEGREES	-41.95 DEGREES	-41.87 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -41.91 DEGREES, DIFFERENCE IN ANGLES = 4.105E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.013372	0.0	0.007443	0.0
2	1.999998	0.001433	0.001432	1.999998
3	-0.016650	0.007705	-0.008129	-0.016378
4	0.002231	0.001059	-0.001573	-0.001561
5	-0.000137	0.000567	-0.000474	0.000817

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 10.21 ARC MINUTES AT 110.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000003	0.0
2	-0.000236	-0.001570
3	0.000047	0.000157
4	-0.000364	0.000231
5	-0.000131	-0.000942

Figure 38. Test Data Summary - 0.9-Inch Engineering Model Pattern Against Standard Pickoff

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18130 041769	EM2Q/EM3P	6.531E-04	2.244E-04	5	5	12301
18230 041769	EM2Q/EM3P	7.443E-04	2.847E-04	7	5	12302
18130 041769	EM2Q/EM3P	6.531E-04	2.244E-04	5	5	12301
18230 041769	EM2Q/EM3P	7.443E-04	2.847E-04	7	5	12302

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.007298	0.0	-0.004233	0.0	0.007298	0.0	0.004233	0.0
2	0.653119	0.757255	0.754375	-0.656444	-0.653119	-0.757255	-0.754375	0.656444
3	-0.003731	-0.008690	-0.008366	0.003404	0.003731	0.008690	0.008366	-0.003404
4	-0.000874	0.000077	-0.000767	-0.000114	0.000874	-0.000077	0.000767	0.000114
5	-0.000129	-0.000271	-0.000044	0.000165	0.000129	0.000271	0.000044	-0.000165

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-49.22 DEGREES	-48.97 DEGREES	-49.22 DEGREES	-48.97 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -49.10 DEGREES, DIFFERENCE IN ANGLES = 1.260E-01 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.014596	0.0	0.008466	0.0
2	1.999993	0.004401	0.004399	1.999994
3	-0.016139	0.009863	-0.009123	-0.015592
4	0.001555	0.000815	-0.001168	-0.001022
5	0.000400	0.000448	0.000009	0.000341

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 10.21 ARC MINUTES AT 100.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000003	0.0
2	-0.000501	-0.000625
3	0.001697	0.000134
4	0.000090	0.000311
5	-0.000085	-0.000643

Figure 39. Test Data Summary - 0.9-Inch Engineering Model Pattern and Pickoff

SECTION X

ERROR ANALYSIS

10.0 SCOPE

In this section, the definition for error, as it relates to this work, is given. The various mechanical and electrical contributions to error are then discussed. Much of the analysis is complex enough to require a computer, and the different computer programs developed to expedite this work are shown.

10.1 GENERAL SOURCES FOR ERROR

The errors and inaccuracies in an electromechanical device of this type are divisible into two classes: mechanical and electrical. Under mechanical error, are included all effects resulting from either mechanical perturbations of structures, or geometrical effects of position and alignment. Electrical error sources include all the effects of non-perfect electronic signal processing.

10.1.1 Mechanical Errors

Mechanical systems may be conveniently characterized by the degrees of freedom possible in their relative or absolute motions. Consider the system composed of pattern and pickoff discs, fixed in space opposite each other and able to rotate with respect to each other. Let this be the z-axis of a coordinate system as shown in figure 40. Ideally, this rotation about the z-axis would be the only permitted degree of freedom in the system, which of course, specifically measures this rotation. No such system is mechanically perfect, and motions along other axes which may contribute errors are possible.

The other possible rotational degrees of freedom are those of either the pattern or the pickoff plates, or both, around a possible axis in the x-y plane. This is defined as pattern or pickoff tilt, and will be discussed under that title.

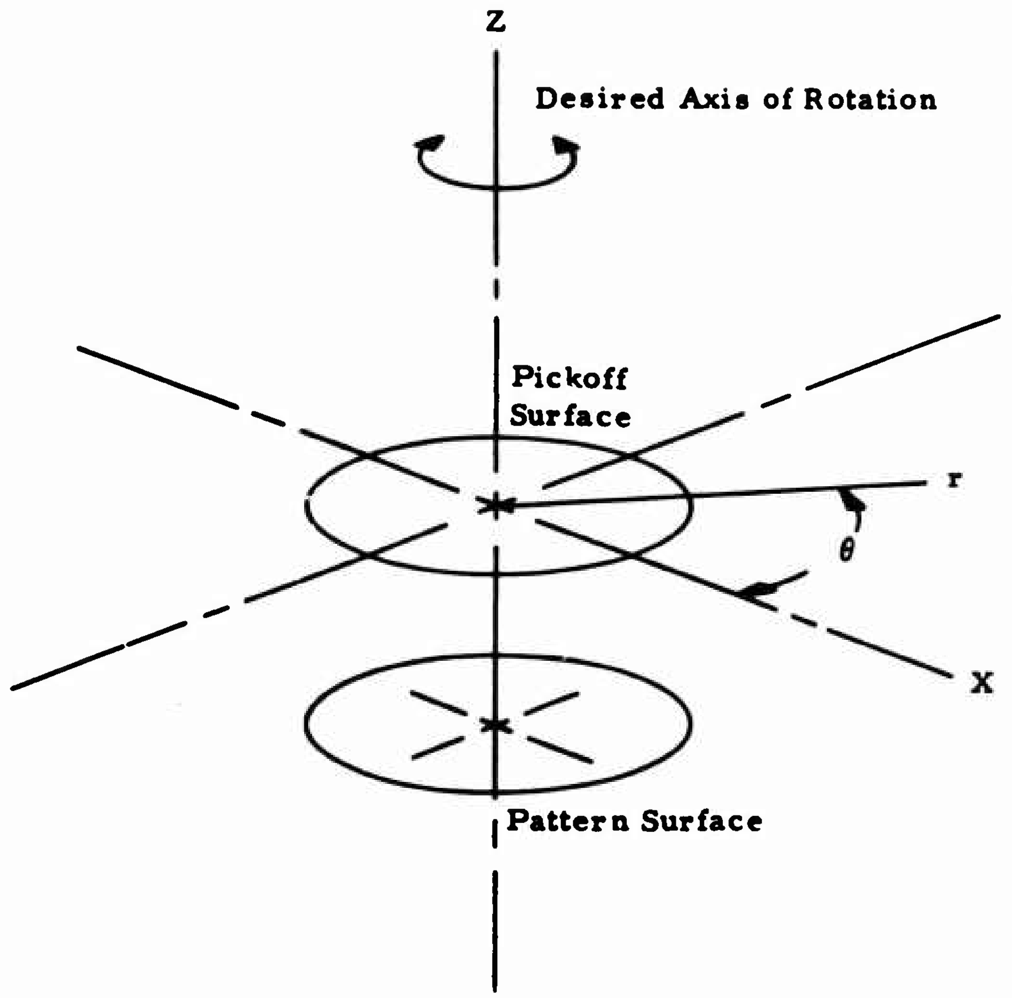


Figure 40. Coordinate System for Error Considerations

The translational degree of freedom along the z-axis does not explicitly give rise to error terms, because of the symmetry of the structures, but any structural irregularities in the z direction will so contribute, and will be considered under the subject of gap changes. Translational motions of either disc in the x-y plane are discussed under eccentricity errors.

10.1.2 Electrical Errors

In the original planning for this work, it was believed that a significant error source would be the effect of fringing fields around the edges of the pattern plate electrodes. In fact, preparation was made for redesigning the pattern on the basis of experimental measurements of this distortion. Experimental results have shown that any such effects appear to be significantly less than the mechanical error discussed here, and hence no further work was done on this topic. The first choice of a three-element pattern was found to be eminently suitable for both the 1.5 and 0.9-inch diameter plates.

There are a number of significant areas which contribute to electronic errors. These electronic errors are: finite amplifier gain, component tolerances, stray capacitance, and parametric effects.

10.1.3 General Expression for Error

Error in the capacitive resolver is defined as follows:

Error = Mechanical Input Angle - Electrical Output Angle

or

$$\theta_e = \theta_{input} - \arctan \left[\frac{a \sin\theta}{b \cos\theta}\right]_{output} \tag{10.1}$$

where a and b are the respective coupling coefficients for the pairs of pickoff plates, and $\sin\theta$ and $\cos\theta$ are the two periodic functions of the angle seen by the pairs of plates.

10.2 MECHANICAL ERROR ANALYSIS

10.2.1 Error Due to Gap Changes Along Pattern

Consider a gap between the pattern and the pickoff plates that is effectively changing along the length of the pattern in some random way. This change is caused by a combination of waviness in the surface of the pattern and nonperpendicularity between the average surface plane and the axes of rotation for either element. Included here are all the surface errors that would cause a gap "runout" and that have no angular correlation to the pattern. This runout effectively changes the local coupling coefficients, a and b, in the error expression; and a change in their ratio introduces error. The error expression is written as follows:

$$\theta_e = \theta - \arctan\ [k \tan\theta] \tag{10.2}$$

where:

$$k = a/b \tag{10.3}$$

The values of θ where this error will be a maximum are calculated from the derivative of error with respect to θ

$$\frac{d\theta_e}{d\theta} = 1 - \frac{k \sec^2\theta}{1 + k^2 \tan^2\theta} = 0 \tag{10.4}$$

or

$$1 - k \sec^2\theta + k^2 \tan^2\theta = 0 \tag{10.5}$$

from which

$$\theta = \arctan \sqrt{\frac{1}{k}} \tag{10.6}$$

so that for $k = 1$, maximum error occurs around $\theta = \pm 45^{\circ}$ and substituting into equation (10.2)

$$\theta_{e_{max}} = \arctan \sqrt{\frac{1}{k}} - \arctan \left(k\sqrt{\frac{1}{k}}\right) \tag{10.7}$$

from which

$$k = \left(\sec \theta_{e_{max}} \pm \tan \theta_{e_{max}}\right)^2 \tag{10.8}$$

This expression can be considered as $k \pm \Delta k$. Defining relative runout as $\Delta g/g_o$, as shown in figure 41, the expression for k can be written:

$$k \pm \Delta k = \frac{a}{b} = \frac{1}{1-\left(\frac{\Delta g}{g_o}\right)^2} \tag{10.9}$$

from which

$$\frac{\Delta g}{g_o} = \pm \sqrt{1 - \frac{1}{k + \Delta k}} \tag{10.10}$$

and for small Δk

$$\frac{\Delta g}{g_o} \approx \sqrt{\Delta k} \tag{10.11}$$

Calculating the relative gap change that will cause a 5 arc minute error in output

$$\theta_e = 5 \text{ arc minutes}$$

$$k = (\sec \theta_e \pm \tan \theta_e)^2 = (1 \pm 0.00145)^2$$

or:

$$k \pm \Delta k = 1 \pm 0.0029$$

and

$$\frac{\Delta g}{g_o} = \pm \sqrt{0.0029} = 0.054$$

so that for a gap (g_o) of 0.003 inches, a random gap change bounded by 0.0003 inches will limit that output error contribution to 5 arc minutes.

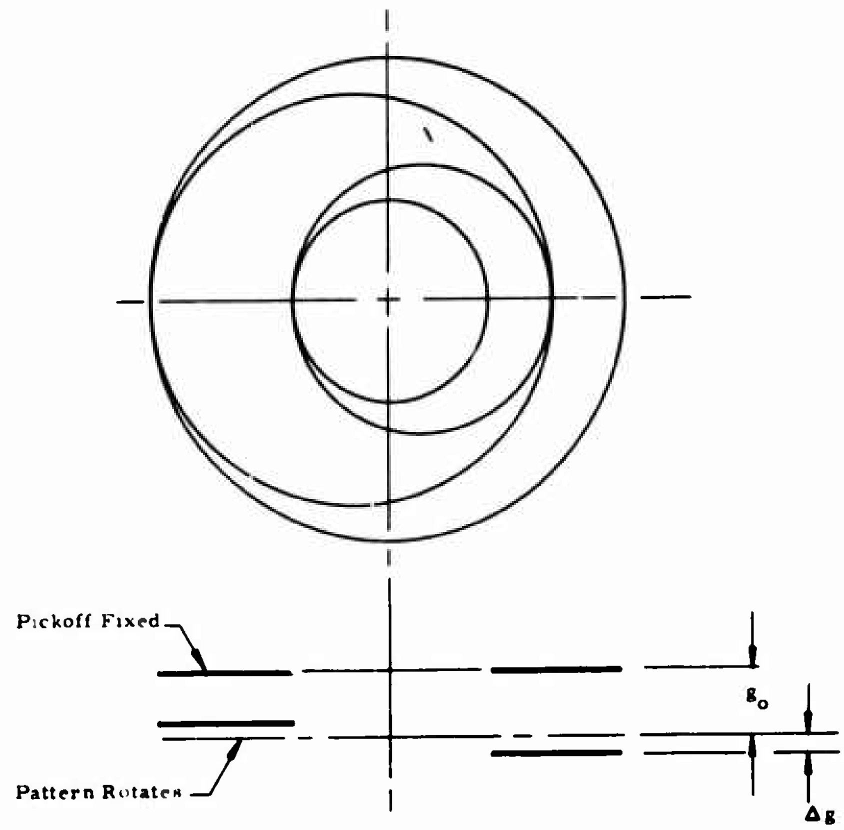


Figure 41. Gap Runout

10.2.2 Error Introduced by Radial Misalignment or Eccentricity

Error is introduced into the output signal of the capacitive resolver if the center of either the pattern or the pickoff is displaced from the axis of pattern rotation. If the pattern and the pickoff are identical in size, any radial displacement of one with respect to the other causes a vignetting of the pattern, and a complex error model is needed to account for the interruption of pattern elements. However, if the pickoff is allowed to be slightly larger than the pattern, so that the pattern boundaries are always inside the pickoff boundaries, radially, then a simpler error model can be constructed that provides a close-form approximate function of the net coupled output signal.

10.2.2.1 Compound Eccentricity Error Model. Consider the relationships of the pattern and pickoff of the capacitive resolver shown in figure 42. The center of the pickoff is displaced eccentrically from the center of pattern rotation and the center of the pattern itself is displaced eccentrically from its center of rotation. This compound eccentricity is the case encountered most often in pattern testing and the error model must deal with this case because the kinematic relationships are dependent on both eccentricities, and cannot be separated. Figure 43 shows this relationship between a line in the pattern coordinate system, (in this case the mean pattern radius, R) and

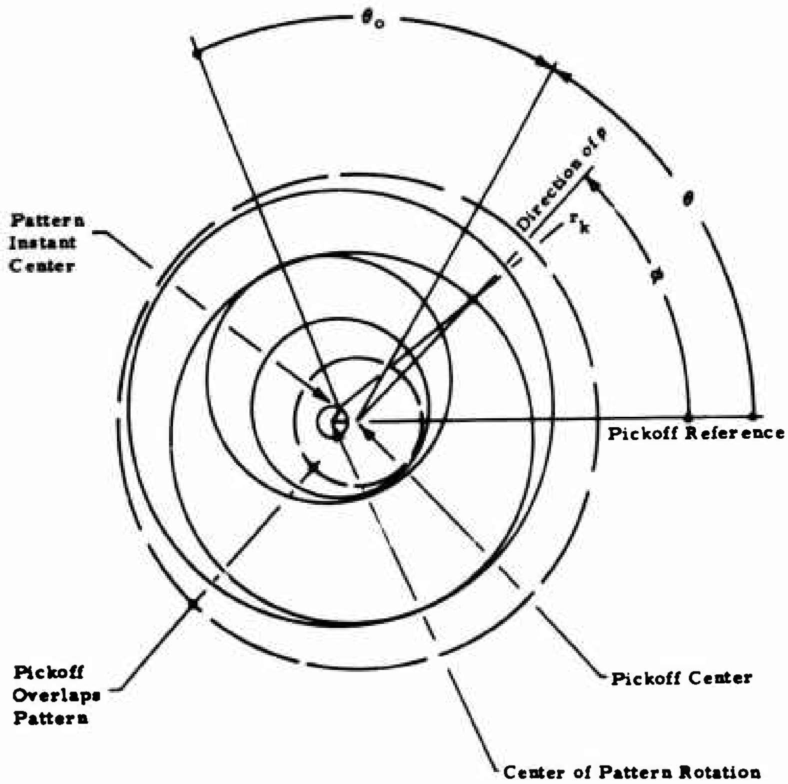


Figure 42. Comp... ınded Eccentricities with Extended-Diameter Pickoff Overlapping Pattern

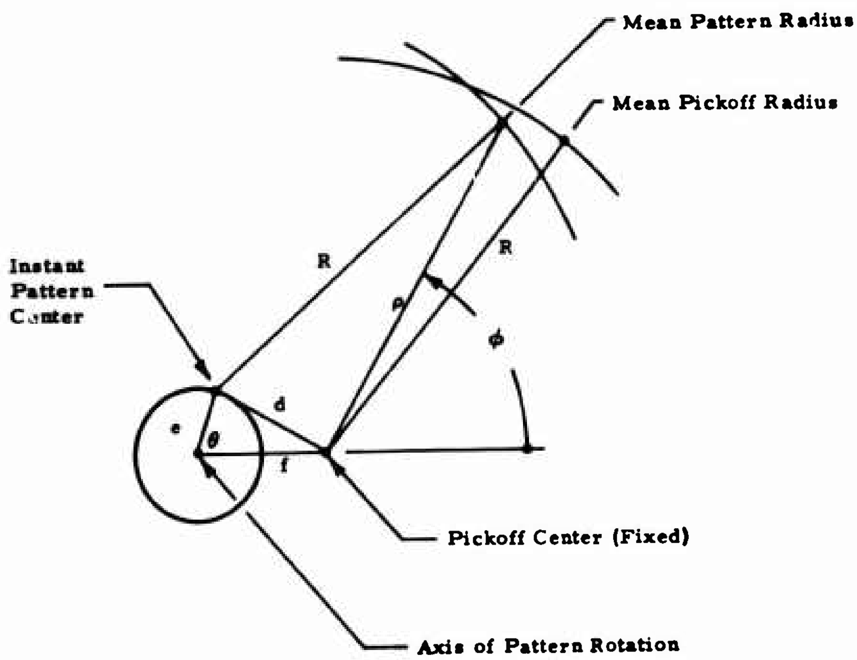


Figure 43. Relationships of Patterns and Pickoff Centers for Compound Eccentricities

that line in the pickoff coordinate system, specified by ρ and ϕ. The two coordinate systems are displaced by d, which changes direction and length as the pattern eccentric, e, is rotated in θ. When d is small in comparison to R, as is the case with the small eccentricities, e and f, the radius, ρ, can be described to second order in terms of the eccentric parameters.

$$\rho = R\left\{1 + \left[\left(\frac{e}{R}\right)\cos(\theta+\phi) - \left(\frac{f}{R}\right)\cos\phi\right] - \frac{1}{2}\left[\left(\frac{e}{R}\right)\sin(\theta+\phi) - \left(\frac{f}{R}\right)\sin\phi\right]^2\right\} \tag{10.12}$$

where e/R and f/R are the normalized pattern and pickoff eccentricities, θ is angle through which the pattern eccentric vector has been rotated, and ϕ is the angle of interest in the pickoff coordinate system. The net coupled signal to a pickoff quadrant is calculated as in the previous sections describing pattern selection, using the relationship stated above to describe pattern generating functions in the pickoff coordinate system. In general:

$$A_{net} = \frac{1}{2}\int_{\phi-\pi/4}^{\phi+\pi/4}\left[\left(\rho_o^{\,2} - \rho_i^{\,2}\right) + 2\left(\rho_i^{\,2} - \rho_k^{\,2}\right)\right]d\phi \tag{10.13}$$

Now, expanding equation (10.12)

$$\rho = r\left\{1 + \left[\left(\frac{e}{R}\cos\theta - \frac{f}{R}\right)\cos\phi - \left(\frac{e}{R}\sin\theta\right)\sin\phi\right] - \frac{1}{2}\left[\left(\frac{e}{R}\cos\theta - \frac{f}{R}\right)\sin\phi + \left(\frac{e}{R}\sin\theta\right)\cos\phi\right]^2\right\} \tag{10.14}$$

and let

$$\left(\frac{e}{R}\right)\cos\theta - \left(\frac{f}{R}\right) = -\alpha$$
$$\left(\frac{e}{R}\right)\sin\theta = \beta \tag{10.15}$$

then

$$\rho = r\left\{1 - (\alpha\cos\phi + \beta\sin\phi) - \frac{1}{2}(\beta\cos\phi - \alpha\sin\phi)^2\right\} \tag{10.16}$$

and to second order

$$\rho^2 = r^2 \Big\{ 1 - 2(\alpha \cos\phi + \beta \sin\phi) + (\beta^2 - \alpha^2) \cos 2\phi + 2\alpha\beta \sin 2\phi \Big\} \tag{10.17}$$

which is used to expand the function being integrated, as shown below:

$$\frac{1}{2}\left[(\rho_o^2 - \rho_i^2) + 2(\rho_i^2 - \rho_k^2)\right] = \left[\frac{1}{2}(r_o^2 - r_i^2) + 2(r_i^2 - r_k^2)\right] + \Big\{ 1 - 2(\alpha \cos\phi + \beta \sin\phi) + (\beta^2 - \alpha^2)\cos 2\phi + 2\alpha\beta \sin 2 \Big\} \tag{10.18}$$

The expression in r^2 is recalled from paragraph 3.2 to be

$$4R^2\epsilon \cos\text{ (pattern angle)}$$

and, referring to figure 42 is:

$$4R^2\epsilon \cos(\theta + \theta_o - \phi) \tag{10.19}$$

Then

$$A_{net} = 4R^2\epsilon \int_{\phi - \pi/4}^{\phi + \pi/4} \cos(\theta + \theta_o - \phi) \Big\{ 1 - 2(\alpha \cos\phi + \beta \sin\phi) + (\beta^2 - \alpha^2)\cos 2\phi + 2\alpha\beta \sin 2\phi \Big\} d\phi \tag{10.20}$$

Integrating over $(\phi \pm \pi/4)$ and summing opposite plates

$$E(\phi) = A_{net}(\phi) - A_{net}(\phi \pm \pi)$$

$$= 8R^2 \epsilon \sqrt{2}\Bigg[\left\{\cos(\theta + \theta_o)\left[1 + \frac{1}{2}(\beta^2 - \alpha^2)\right] - \alpha\beta \sin(\theta + \theta_o)\right\}\cos\phi$$

$$+ \left\{\sin(\theta + \theta_o)\left[1 - \frac{1}{2}(\beta^2 - \alpha^2)\right] - \alpha\beta\cos(\theta + \theta_o)\right\}\sin\phi \qquad (10\ 21)$$

$$+ \frac{1}{3}\left\{\frac{1}{2}(\beta^2 - \alpha^2)\cos(\theta + \theta_o) + \alpha\beta \sin(\theta + \theta_o)\right\}\cos 3\phi$$

$$+ \frac{1}{3}\left\{\frac{1}{2}(\beta^2 - \alpha^2)\sin(\theta + \theta_o) - \alpha\beta\cos(\theta + \theta_o)\right\}\sin 3\phi\Bigg]$$

finally, substituting for α and β and collecting on terms in θ

$$E(\phi, \theta) = \frac{1}{3}\left(\frac{e}{R}\right)\left(\frac{f}{R}\right)\cos(\theta_o - 3\phi)$$

$$+ \left\{\cos(\theta_o - \phi) - \frac{1}{2}\left(\frac{f}{R}\right)^2 \sin(\theta_o + \phi) - \frac{1}{6}\left[\left(\frac{e}{R}\right)^2 + \left(\frac{f}{R}\right)^2\right]\cos(\theta_o - 3\phi)\right\}\cos\theta$$

$$+ \left\{-\sin(\theta_o - \phi) + \frac{1}{2}\left(\frac{f}{R}\right)^2 \sin(\theta_o + \phi) - \frac{1}{6}\left[\left(\frac{e}{R}\right)^2 - \left(\frac{f}{R}\right)^2\right]\sin(\theta_o - 3\phi)\right\}\sin\theta$$

$$+ \left(\frac{e}{R}\right)\left(\frac{f}{R}\right)\cos(\theta_o + \phi)\cos 2\theta - \left(\frac{e}{R}\right)\left(\frac{f}{R}\right)\sin(\theta_o + \phi)\sin 2\theta - \frac{1}{2}\left(\frac{e}{R}\right)^2$$

$$\cos(\theta_o + \phi)\cos 3\theta + \left(\frac{e}{R}\right)^2 \sin(\theta_o + \phi)\sin 3\phi \qquad (10.22)$$

This expression $E(\phi, \theta)$ relates the output function to arbitrary eccentric displacement away from the center of rotation of both the pattern and the pickoff.

10.2.2.2 Computer-Aided Eccentricity Error Analysis. A computer program was written to calculate the maximum error that is introduced by a combination of pattern and pickoff eccentricities. The equation of the preceding section is used to calculate the Fourier coefficients, and these are used to initialize a computer routine similar to DFCAP4 described in section VI. The program is designated DOCAP, and operates in two modes. In the first mode, the normalized eccentricities of interest are entered from the keyboard of a remote (control) console of the computer, and the program searches through the angular relationships to find the maximum error and identify its position parameters. A specimen output format of this program is shown in figure 44.

```
EXPECTED ERROR IN CAPACITIVE RESOLVER OUTPUT DUE TO ECCENTRICITIES E/R AND F/R
ENTER ECCENTRICITIES IN THE FIELDS INDICATED (FROM THE KEYBOARD IN FLOATING POINT REAL NUMBERS)


   E/R       F/R       ERROR FCN MAX    AT ANGLE OF    COMPUTED BIAS   PATTERN BIAS    PICKOFF BIAS
 '       ''        '    (ARCMINUTES)     THETA(DEG)      PSI(DEG)      THETA-0(DEG)      PHI(DEG)
 _ 0.1
                          17.2219         345.000        90.04781        165.000          75.000


   E/R       F/R       ERROR FCN MAX    AT ANGLE OF    COMPUTED BIAS   PATTERN BIAS    PICKOFF BIAS
 '       ''        '    (ARCMINUTES)     THETA(DEG)      PSI(DEG)      THETA-0(DEG)      PHI(DEG)
 _ 0.0       0.1
                          11.4649          90.000       -44.99995          0.0            45.000


   E/R       F/R       ERROR FCN MAX    AT ANGLE OF    COMPUTED BIAS   PATTERN BIAS    PICKOFF BIAS
 '       ''             (ARCMINUTES)     THETA(DEG)      PSI(DEG)      THETA-0(DEG)      PHI(DEG)
 _ 0.1       0.1
                          63.0355         315.000       134.90439        135.000           0.0
```

Figure 44. Specimen of Output Format of Computer Program DOCAP (Manual Mode)

The program resets after each computation and accepts new values of eccentricities. The second mode of operation is under the control of a preset increment for both normalized eccentricities and the output format in this mode is an array of values of expected error introduced by these incremental values of eccentricity. A specimen output format for this program mode is shown in figure 45.

10.2.3 Error Introduced by Angular Misalignment or Tilt

Error is introduced into the output signal of the capacitive resolver when either the pattern or pickoff surfaces are displaced from planes parallel to each other and normal to the axis of rotation.

10.2.3.1 Pattern Tilt Error Model. Consider the relationships between the three element pattern and the pickoff shown in figure 46. The pattern surface is shown to be tilted out of a plane normal to its axis of rotation by the angle α, and in a direction μ from the zero point of the pattern generating functions. The pattern is displaced from an arbitrary pickoff reference by the angle θ, and the pattern and pickoff surfaces are separated by an average gap, g_o. The net signal coupled into a pickoff quadrant is proportional to the net area of pattern spanned by the pickoff and is inversely proportional to the gap.

EXPECTED ERROR IN CAPACITIVE RESOLVER OUTPUT DUE TO ECCENTRICITIES E/R AND F/R (ERROR IN ARCMINUTES)

E/R F/R	0.0	0.010	0.020	0.030	0.040	0.050	0.060	0.070	0.080	0.090	0.100
0.0	0.0	0.16	0.61	1.35	2.39	3.73	5.38	7.32	9.57	12.12	14.98
0.010	0.11	0.60	1.45	2.60	4.04	5.78	7.83	10.16	12.80	15.74	18.98
0.020	0.40	1.15	2.40	3.95	5.79	7.94	10.38	13.13	16.17	19.51	23.16
0.030	0.90	1.80	3.45	5.40	7.65	10.20	13.04	16.19	19.63	23.39	27.44
0.040	1.60	2.66	4.60	6.95	9.60	12.55	15.80	19.35	23.20	27.36	31.81
0.050	2.49	3.78	5.85	8.60	11.65	15.00	18.65	22.61	26.87	31.42	36.29
0.060	3.58	5.10	7.20	10.35	13.80	17.55	21.61	25.96	30.62	35.59	40.86
0.070	4.87	6.62	8.67	12.21	16.05	20.20	24.65	29.42	34.48	39.85	45.53
0.080	6.36	8.34	10.63	14.16	18.41	22.95	27.80	32.97	38.43	44.21	50.29
0.090	8.05	10.26	12.77	16.22	20.87	25.80	31.04	36.61	42.48	48.66	55.15
0.100	9.93	12.37	15.12	18.37	23.43	28.77	34.40	40.34	46.62	53.21	60.10

Figure 45. Specimen of Output Format of Computer Program DOCAP (Incremental Mode)

The gap is varied with pattern rotation and with radial displacement from the center of rotation:

$$g = g_o - \rho \sin \alpha \cos (\theta + \mu - \phi) \tag{10.23}$$

where ϕ is the angular displacement of ρ from the pickoff reference. The output signal then is proportional to

$$\frac{A_{net}}{g_o} = \int_{\phi - \pi/4}^{\phi + \pi/4} \int_{\rho_1}^{\rho_2} \left[\frac{\rho \, d\rho}{g_o - \rho \sin \alpha \cos (\theta + \mu - \phi)} \right] d\phi \tag{10.24}$$

for small α, this exact function is approximated by

$$\frac{A_{net}}{g_o} = \int_{\phi - \pi/4}^{\phi + \pi/4} \int_{\rho_1}^{\rho_2} \rho \left[g_o + \rho\alpha \cos (\theta + \mu - \phi) \right] d\rho d\phi \tag{10.25}$$

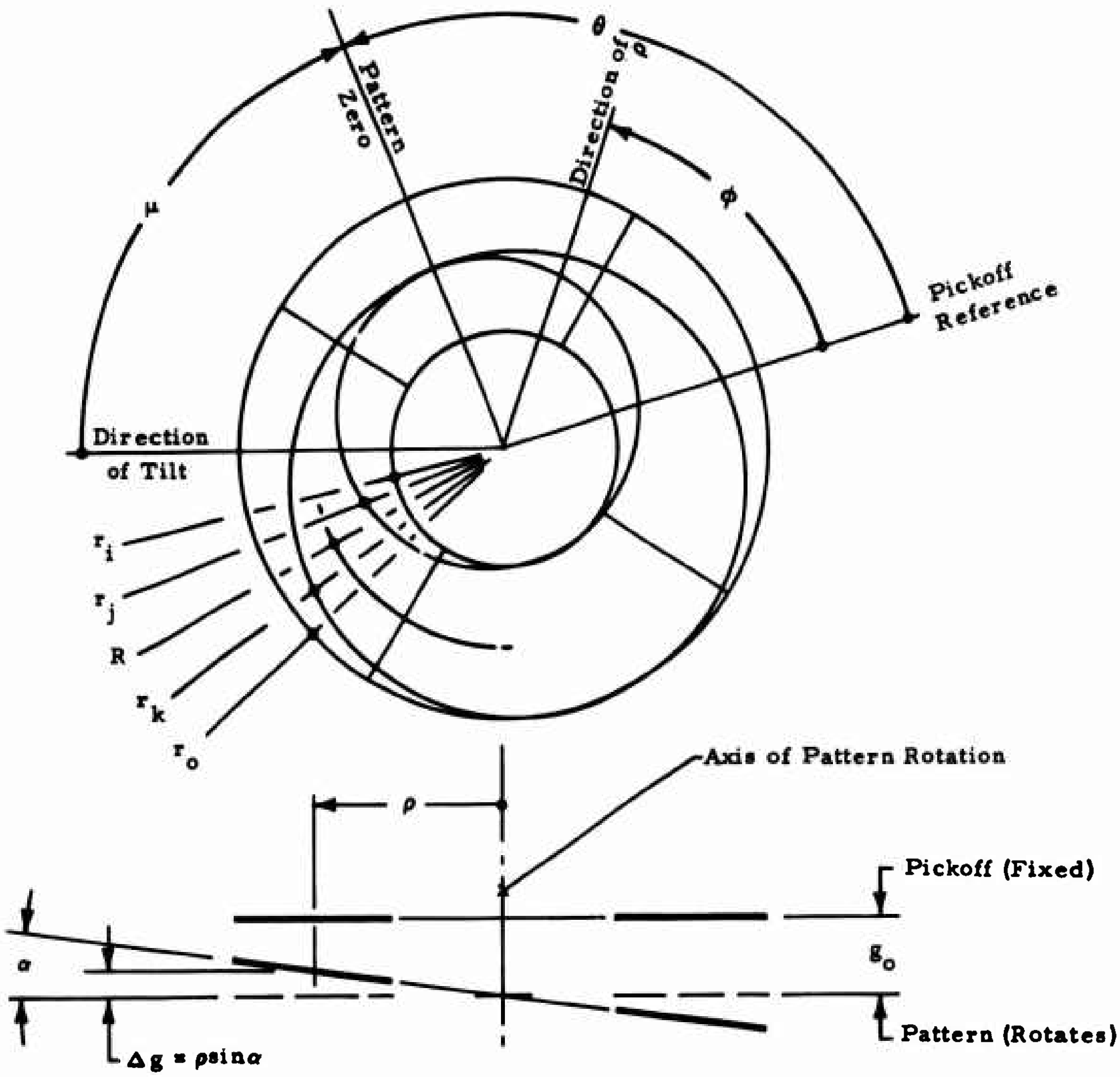


Figure 46. Pattern Tilt Geometry

Integrating over ρ and taking the limits of the pattern generating functions

$$\frac{A_{net}}{g_o} = \frac{1}{g_o^2}\int_{\phi - \pi/4}^{\phi + \pi/4}\left\{ \frac{1}{2} g_o \left[(r_o^2 - r_i^2) - 2 (r_k^2 - r_j^2)\right] + \frac{1}{3}\alpha \cos (\theta + \mu - \phi) \left[(r_o^3 - r_i^3) - 2 (r_k^3 - r_j^3)\right]\right\} d\phi \qquad (10.26)$$

Substituting the generating functions, integrating over φ, and summing the signals from opposite plates.

$$\frac{E}{g_o}(\phi) = \frac{A}{g_o}\text{net}(\phi) - \frac{A}{g_o}\text{net}(\phi \pm \pi)$$

$$= \frac{8R^2\epsilon}{g_o}\left[\sin(\theta - \phi) + \frac{1}{3}\bar{\alpha}\epsilon^2\left\{\cos\mu \sin^3(\theta - \phi)\right.\right. \tag{10.27}$$

$$\left.\left.\left. + \sin\mu\left[3\cos(\theta - \phi) - \cos^3(\theta - \phi)\right]\right\}\right]\right|_{\phi - \pi/4}^{\phi + \pi/4}$$

where:

$$\bar{\alpha} = \frac{\alpha R}{g_o} = \frac{\Delta g}{g} \tag{10.28}$$

Evaluating the expression for a general case ϕ

$$\frac{E}{g_o}(\phi) = \frac{8R^2\epsilon}{g_o}\sqrt{2}\left[\cos(\theta - \phi) + \frac{1}{12}\bar{\alpha}\epsilon^2\left\{\cos\mu\left[3\cos(\theta - \phi) - \cos 3(\theta - \phi)\right]\right.\right. \tag{10.29}$$

$$\left.\left. - \sin\mu\left[9\sin(\theta - \phi) - \sin 3(\theta - \phi)\right]\right\}\right]$$

Assuming that the cosine plates are centered on the pickoff reference, the two output signals are proportional to:

$$E_{cos} = \cos\theta + \frac{1}{12}\bar{\alpha}\epsilon^2\left[\cos\mu(3\cos\theta - \cos 3\theta)\right.$$

$$\left. - \sin\mu(9\sin\theta - \sin 3\theta)\right] \tag{10.30}$$

$$E_{sin} = \sin\theta + \frac{1}{12}\bar{\alpha}\epsilon^2\left[\cos\mu(3\sin\theta + \sin 3\theta)\right.$$

$$\left. + \sin\mu(9\cos\theta + \cos 3\theta)\right]$$

The errors are seen to be proportional to the pattern relative tilt ($\bar{\alpha}$) and the direction of the tilt from pattern zero (μ), and are a combination of single and three-speed terms in pattern angle of rotation.

10.2.3.2 <u>Pickoff Tilt Error Model.</u> Consider the relationship between the three-element pattern and the pickoff shown in figure 47. The pickoff surface is shown to be rotated out of a plane normal to the pattern axis of rotation by the angle β, in a direction σ from the arbitrary pickoff reference. The zero point of the pattern generating function is displaced from the pickoff reference by the angle θ. The gap between pattern and pickoff varies with ϕ, and with the displacement from the center of rotation;

$$g = g_o - \rho \sin \beta \cos (\sigma - \phi) \tag{10.31}$$

The net signal, as before is

$$\frac{A_{net}}{g_o} = \int_{\phi - \pi/4}^{\phi + \pi/4} \int_{\rho_1}^{\rho_2} \left[\frac{\rho \, d\rho}{g_o - \rho \sin \beta \cos (\sigma - \phi)} \right] d\phi \tag{10.32}$$

and for small β, is approximated by

$$\frac{A_{net}}{g_o} = \int_{\rho_1}^{\rho_2} \int_{\phi - \pi/4}^{\phi + \pi/4} \rho \left[g_o + \rho\beta \cos (\sigma - \phi) \right] d\rho \, d\phi \tag{10.33}$$

Proceeding as with pattern tilt, the net summed signal is:

$$\frac{E}{g_o}(\phi) = \frac{8R^2\epsilon}{g_o} \Bigg[\sin(\theta - \phi) + \frac{1}{12} \bar{\beta} \epsilon^2 \Big\{ \cos(\sigma - \theta) \left[3 \sin(\theta - \phi) - \sin 3(\theta - \phi) \right] + \sin(\sigma - \theta) \left[9 \cos(\theta - \phi) - \cos 3(\theta - \phi) \right] \Big\} \Bigg] \tag{10.34}$$

Assuming again that the cosine plates are centered on the pickoff reference, the two output signals are proportional to:

$$\begin{aligned} E_{cos} &= \cos \theta + \frac{1}{12} \bar{\beta} \epsilon^2 \left[\cos \sigma (6 - 4 \cos 2\theta) - 2 \sin \sigma \sin 2\theta \right] \\ E_{sin} &= \sin \theta + \frac{1}{12} \bar{\beta} \epsilon^2 \left[\sin \sigma (6 + 4 \cos 2\theta) - 2 \cos \sigma \cos 2\theta \right] \end{aligned} \tag{10.35}$$

The errors are seen to be proportional to the pickoff relative tilt ($\bar{\beta}$) and the direction of the tilt from the center of the cosine plates (σ), and are a combination of zero-speed and two-speed terms in pattern angle of rotation.

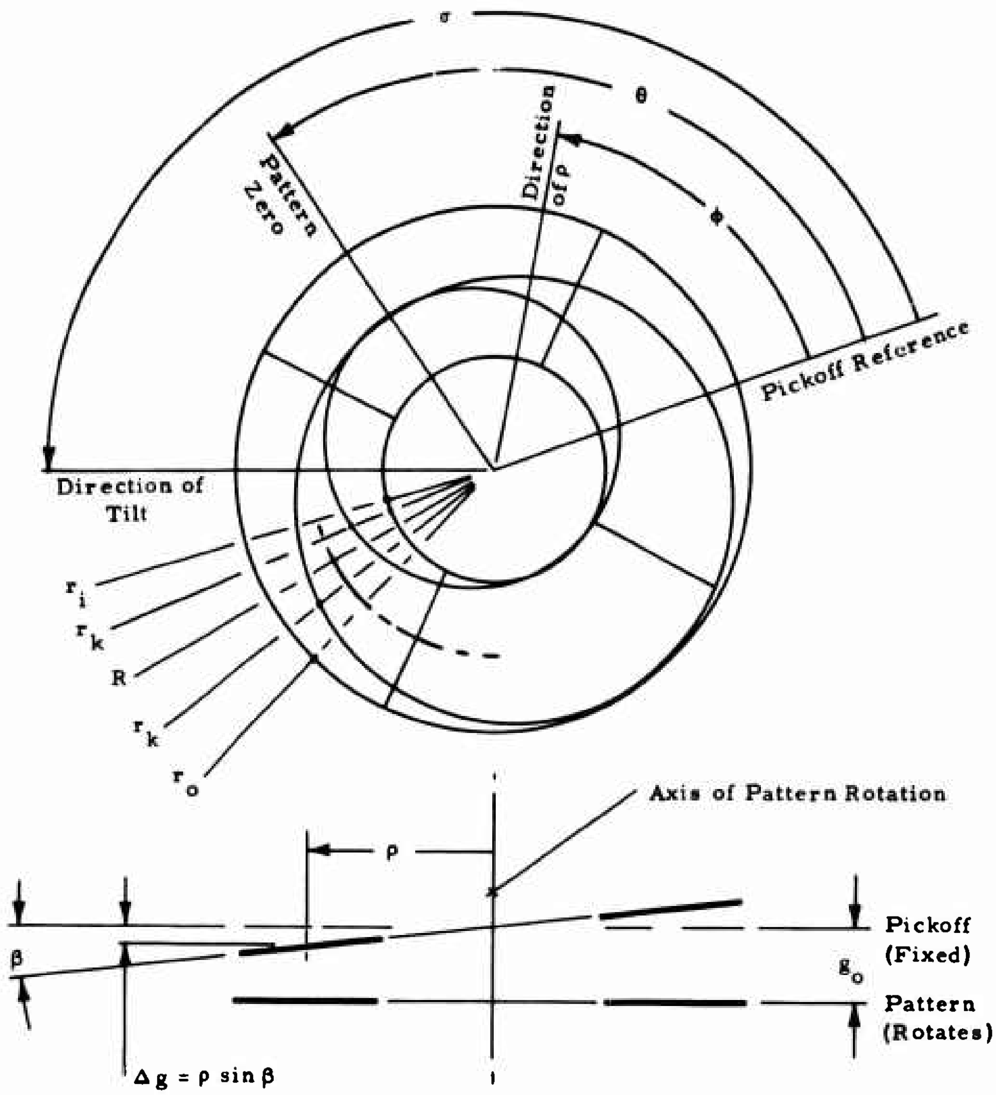


Figure 47. Pickoff Tilt Geometry

10.2.3.3 Combined Tilt. Combined pattern and pickoff tilt is simply a linear combination of the two tilts taken separately. Consider the common reference points shown in figure 48. The gap at any angular displacement from the arbitrary pickoff reference is:

$$g = g_o - \rho \sin \alpha \cos (\theta + \mu - \phi) - \rho \sin \beta \cos (\sigma - \phi) \tag{10.36}$$

and for small α and β, the net coupled signal is:

$$\frac{A_{net}}{g_o} = \int_{\phi - \pi/4}^{\phi + \pi/4} \int_{\rho_1}^{\rho_2} \rho \left\{ g_o + \rho \left[\alpha \cos (\theta + \mu - \phi) + \beta \cos (\sigma - \phi) \right] \right\} d\rho \, d\phi \tag{10.37}$$

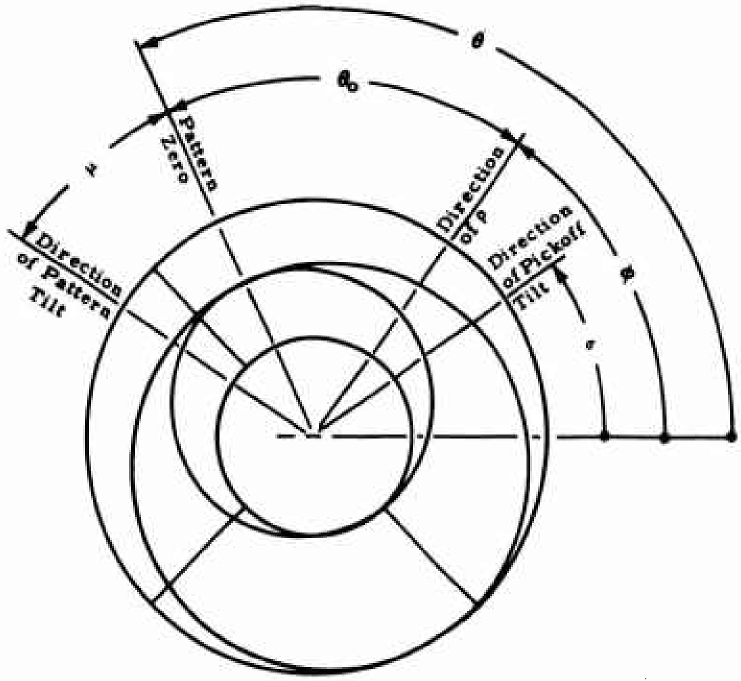


Figure 48. Angular Relationships for Combined Pattern and Pickoff Tilt

The analysis follows, as before, and the two output signals are proportional to:

$$
\begin{aligned}
E_{cos} &= \cos \phi + \frac{1}{12}\overline{\alpha}\,\epsilon^2 \left[\cos \mu\,(3 \cos \theta - \cos 3\theta) - \sin \mu\,(9 \sin \theta - \sin 3\theta)\right] \\
&\quad + \frac{1}{12}\overline{\beta}\,\epsilon^2 \left[\cos \sigma\,(6 - 4 \cos 2\theta) - 2 \sin \sigma \sin 2\theta\right] \\
E_{sin} &= \sin \theta + \frac{1}{12}\overline{\alpha}\,\epsilon^2 \left[\cos \mu\,(3 \sin \theta + \sin 3\theta) \sin \mu\,(9 \cos \theta + \cos 3\theta)\right] \\
&\quad + \frac{1}{12}\overline{\beta}\,\epsilon^2 \left[\sin \sigma\,(6 + 4 \cos 2\theta) - 2 \cos \sigma \sin 2\theta\right]
\end{aligned}
\qquad (10.38)
$$

10.2.3.4 Computer-Aided Tilt Error Analysis. A computer program was written to calculate the maximum error that is introduced by the combination of pattern and pickoff tilt. The equations of the previous paragraph are used to calculate the Fourier coefficients, and these are used to initialize a routine similar to DFCAP4, described in section VI. The program, designated DOTLT, operates in two modes. In the first mode, the relative tilts of interest are entered from the keyboard of the remote (control) console of the computer, and the program searches through the angular

relationships to find a maximum error and identify its position parameters. A specimen output format of this program is shown in figure 49. The program resets after each computation, and accepts new values of tilt.

```
EXPECTED ERROR IN OUTPUT OF CAPACITIVE RESOLVER DUE TO RELATIVE TILTS OF PATTERN (ALPHA) AND PICKOFF (BETA)
ENTER RELATIVE TILTS ALPHA AND BETA IN FIELDS INDICATED (FROM KEYBOARD IN FLOATING POINT REAL NUMBERS)

 ' ALPHA   '' BETA   '  MAXIMUM ERROR   AT ANGLE OF      DIRECTION OF TILTS CAUSING MAX ERROR(DEGREES)
                         (ARC MINUTES)  THETA (DEG)    FROM PATTERN ZERO (MU)   FROM COSINE PLATE (SIGMA)
 _  0.1
                          0.9344         330.0              30.0                        0.0

 ' ALPHA   '' BETA   '  MAXIMUM ERROR   AT ANGLE OF      DIRECTION OF TILTS CAUSING MAX ERROR(DEGREES)
                         (ARC MINUTES)  THETA (DEG)    FROM PATTERN ZERO (MU)   FROM COSINE PLATE (SIGMA)
 _  0.0      0.1
                          9.2847          90.0               0.0                        0.0

 ' ALPHA   '' BETA   '  MAXIMUM ERROR   AT ANGLE OF      DIRECTION OF TILTS CAUSING MAX ERROR(DEGREES)
                         (ARC MINUTES)  THETA (DEC)    FROM PATTERN ZERO (MU)   FROM COSINE PLATE (SIGMA)
 _  0.1      0.1
                         10.2100           0.0              90.0                       90.0
```

Figure 49. Specimen Output Format for Computer DOTLT (Manual Mode)

The second mode of operation is under the control of a preset increment for both relative tilts, and the output format is an array of values of expected error introduced by these incremental values of tilt. A specimen output format for this program mode is shown in figure 50.

10.2.3.5 Special Case of Pattern Tilt Error in a Single Pickoff Quadrant. The error introduced into the net coupled signal of a single pickoff quadrant, due to pattern tilt, is included here because it is the basis for the "least squares" calculation to separate tilt error in the data reduction computer program DFCAP4. The analysis follows the scheme of the pattern tilt calculation in paragraph 10.2.3.1, departing at the point where opposite plate signals are summed. In the special case calculation, both even and odd terms are retained and the resulting output signal is proportional to:

$$
\begin{aligned}
E_{cos} = \cos\theta + \frac{1}{12}\,\overline{\alpha}\Bigg\{&\cos\mu\left[\frac{3\pi\sqrt{2}}{8}\,(4 + 5\epsilon^2) + 3\epsilon^2\cos\theta\right.\\
&\left.+\ 2\,(3 + 4\epsilon^2)\cos 2\theta - \epsilon^2\cos 3\theta\right] - \sin\mu\left[9\epsilon^2\sin\theta\right.\\
&\left.+\frac{\sqrt{2}}{2}\,(6 + 7\epsilon^2)\sin 2\theta - \epsilon^2\sin 3\theta\right]\Bigg\}
\end{aligned}
\qquad (10.39)
$$

EXPECTED ERROR IN OUTPUT OF CAPACITIVE RESOLVER DUE TO RELATIVE TILTS OF PATTERN (ALPHA) AND PICKOFF (BETA)

ALPHA / BETA	0.0	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200
0.0	0.0	0.19	0.38	0.56	0.75	0.93	1.12	1.30	1.49	1.68	1.86
0.020	1.86	2.04	2.23	2.41	2.60	2.78	2.97	3.16	3.34	3.53	3.71
0.040	3.72	3.90	4.08	4.27	4.46	4.64	4.83	5.01	5.20	5.38	5.57
0.060	5.57	5.75	5.94	6.13	6.31	6.50	6.68	6.87	7.05	7.24	7.43
0.080	7.43	7.61	7.80	7.98	8.17	8.35	8.54	8.72	8.91	9.10	9.28
0.100	9.28	9.47	9.65	9.84	10.02	10.21	10.40	10.58	10.77	10.95	11.14
0.120	11.14	11.32	11.51	11.70	11.88	12.07	12.25	12.44	12.62	12.81	12.99
0.140	13.00	13.18	13.37	13.55	13.74	13.92	14.11	14.29	14.48	14.66	14.85
0.160	14.85	15.04	15.22	15.41	15.59	15.78	15.96	16.15	16.34	15.52	16.71
0.180	16.71	16.89	17.08	17.26	17.45	17.64	17.82	18.01	18.19	18.38	18.56
0.200	18.57	18.75	18.93	19.12	19.31	19.49	19.68	19.86	20.05	20.23	20.42

Figure 50. Specimen of Output Format for Computer Program DOTLT (Incremental Mode)

A comparison of this output function and the one of paragraph 10.2.3.1 provides a basis for establishing the criteria for gain matching in the signal processing electronics.

10.3 ELECTRICAL ERROR ANALYSIS

10.3.1 Electronic Errors

Electronic errors may be introduced by rewriting the general expression for error, equation (10.1)

$$\theta_e = \theta_{in} - \arctan\left(K \frac{\sin \theta}{\cos \theta}\right)$$

where $k = \frac{a}{b}$, and noting that the factor k contains the electronic gain factors. It may be written as:

$$K = \frac{a}{b} = \frac{G_{p1} G_{s1} + G_{p3} G_{s3}}{G_{p2} G_{s2} + G_{p4} G_{s4}} \qquad (10.40)$$

where the G_p terms are the gains of the preamplifier stages and the G_s terms, the gains of the subtractor stages for the corresponding inputs. (It is assumed here that pickoff plates 1 and 3 are sine; 2 and 4 are cosine.) The input capacity coupling terms here are all considered unity, as their variation would be a geometric effect considered under the mechanical error analysis.

It is also assumed now that in practical use of this device the factor k would be set to unity by an adjustment in some exterior signal processing electronics, and hence the problem may be stated: What would be the deviations in k as a result of non-perfect electronics?

Note first that k is a ratio, and hence more concern is with keeping the ratio constant rather than in the absolu' variation of its components. The sine and cosine amplifier sets are identical and, therefore, the tracking between the amplifier sets is of concern. From paragraph 10.2.1, it is noted that an error of 5 arc minutes is produced by a change in k of 0.3 percent.

10.3.2 Finite Amplifier Gain

The effects of gain changes are first observed in the operational amplifiers. The relative gain changes $\Delta G/G$ in an inverting operational amplifier configuration are given by:

$$\frac{\Delta G}{G} = \frac{\Delta A}{A} \quad \frac{1}{1 + A\beta} \qquad (10.41)$$

where $\Delta A/A$ is the relative gain change of the operational amplifiers. For the input stage employed here:

$$A\beta = \frac{5s + 1}{s(11s + 1)}$$

from which

$$\frac{1}{1 + A\beta} = \frac{11s^2 + s}{11s^2 + 6s + 1}$$

and evaluation at 100 Khz gives:

$$\left| \frac{1}{1 + A\beta} \right| = 0.046$$

showing that the effects of operational amplifier gain change are reduced by a factor of 20.

The LM101 data sheet shows that the chief contributor to gain change is temperature; a change from 25°C to 125°C decreases the gain by about 9 db. If this change in gain is assumed to be linear with temperature, it is a change of -2.8% per °C, and gives an input stage $\Delta G/G$ of -0.13% per °C.

A similar evaluation for the subtractor stage, using $A\beta = 1/2S$ gives a value for the gain reduction factor of 0.124 and a resultant temperature coefficient of -0.35% per °C.

It is reasonable to assume that the trackability of these coefficients is at least an order of magnitude better than this. The usual environment for resolvers in gyro guidance systems is temperature controlled to better than a few degrees, and thus the change in k from this temperature coefficient should be on the order of 0.1 percent.

The dependence of the LM101 gain upon its power supply voltage is about 4% per volt. However, power supply voltage regulation to better than 0.1% is common. Such regulation would reduce the gain uncertainties to 0.06% or less, and this effect can be ignored.

10.3.3 Passive Component Tolerances

The main concern here is the thin film resistor network used in the subtractor stage of the operational amplifiers. Here again, concern is with trackability, and Litton's experience with this type of network shows that the percentage difference of temperature coefficient from one resistor to another on the same substrate less than 5 ppm. In addition, extensive aging experiments indicate that drift in the ratio of resistors on a substrate is less than 0.1% per thousand hours at ambient temperatures up to and including 125°C.

The capacitors used in the electronics package are for operational amplifier frequency compensation and for high-frequency roll-off, and thus their variations would introduce second or higher order effects, and are not treated here.

10.3.4 Stray Capacitance Effects

It has previously been asserted that the operational amplifier approach to the input stage reduces the effects of stray capacitance considerably. To evaluate these effects, the transfer function for the input stage is rewritten, keeping explicit the term including the stray capacitance, C_3 (see figure 25):

$$A(s) = \frac{1}{s}, \quad \beta(s) = \frac{SRC_2 + 1}{SR(C_1 + C_2 + C_3) + 1} = \frac{5S + 1}{9S + RC_3 S + 1}$$

$$\frac{Z_f}{Z_i} = \frac{4S}{5S + 1}$$

$$G(s) = -\frac{Z_f}{Z_i} \cdot \frac{1}{1 + \frac{1}{A\beta}} = -\frac{4S}{9S^2 + RC_3 S^2 + 6S + 1}$$

Let $S = j\omega$

$$G(j\omega) = - \frac{j4\omega}{(1 - g\omega^2 - \omega^2 RC_3) + j6\omega}$$

At 100 Khz, $\omega = 0.0628$, $\omega^2 = 0.00393$, and

$$\left| G \right| 100 \text{ Khz} = \frac{0.255}{\left[1.07 - 0.004 \, RC_3 + 0 \, (RC_3)^2\right]^{1/2}}$$

The scaled numerical value of RC_3 is about 2; hence, the squared term is disregarded and the denominator is expanded in a power series in RC_3 to obtain

$$\left| G \right| 100 \text{ Khz} = 0.245 \left[1 + 0.002 \, RC_3 + \ldots\right]$$

or a fractional change in the stray capacitance will effect the gain by only 1/500 as much as the capacitance change.

10.3.5 Parametric Errors

It should be noted here that this analytical study of the electronics has been the development of a conventional circuit transfer function. The independent variable is an input voltage. It is desired to find the output voltage in terms of various active and passive circuit elements. The theory assumes that all the passive elements are lumped, linear, constant, and bilateral, and that the output voltage is a linear function of the input voltage, related by the transfer function. The actual circuitry, however, does not quite satisfy these conditions. The true input voltage to the pattern plates is constant and the signal is varied by varying a capacitance. It is reasonable to inquire now as to the effect of this distinction on the results. One of the circuit parameters is being varied, and this may be regarded as a "parametric" effect.

A convenient way of handling this is to rewrite the transfer function of the input stage, and keep the dependence upon this capacity explicit:

$$\left.\begin{aligned} A(s) &= \frac{1}{s} \\ \beta(s) &= \frac{5S + 1}{SRC_t + 1} \\ \frac{Z_f}{Z_i} &= \frac{SRC_t}{5S + 1} \end{aligned}\right\} \qquad \begin{aligned} RC_t &= RC_1 + 7 \\ RC_1 \big|_{max} &= 4 \end{aligned}$$

$$G(s) = \frac{SRC_1}{S^2RC_t + 6S + 1}$$

Let $s = j\omega$

$$G(j\omega) = \frac{j\omega RC_1}{1 - 7\omega^2 - \omega^2 RC_1 + j6\omega}$$

At 100 Khz, $\omega = 0.0628$, $\omega^2 = 0.00393$

$$\left|G\right| 100\ \text{Khz} = \frac{0.0628\ RC_1}{1.04\left[1 - 0.007\ RC_1 + (14.3)10^{-6}\ (RC_1)^2\right]^{1/2}}$$

$$\cong 0.0603\ RC_1\left[1 + \frac{0.007\ RC_1 - 14.3.10^{-6}\ x^2}{2} +\ldots\right]$$

$$\cong 0.0603\left[RC_1 + 0.0035\ (RC_1)^2 + \ldots\right]$$

from which it is observed that there is a second order effect in the gain expression. The worst case is for RC_1 at its maximum of about 4, when there would be a 1.4 percent contribution to gai from the second order term.

In practice, C_1 is the total capacitance between a pickoff quadrant and the elements of the pattern plate, and would, therefore, be a constant if there were no mechanical misalignment of the electrode system. Such misalignments would introduce first order changes in the capacitance itself, and these variations (treated under mechanical error) would overshadow any parametric effects, which can be considered second or higher order and may, therefore, be neglected.

10.4 SUMMARY OF ERRORS

The ideal resolver system studied here would deliver as its electrical output sine and cosine functions in the form of pure sinusoids of known amplitude and phase angle. The errors discussed here modify these output functions in various ways. In general, it can be said that errors distort the output function by introducing a d-c component and harmonic terms, both at the fundamental (or first speed) rotational rate of the resolver and at various harmonics of the fundamental rate. Each distortion term will have its own amplitude and phase angle, related to the relative orientation of the various error sources. It is possible to write out a complete expression for the sum of all the error terms considered above, but this would be extremely involved and would serve no useful purpose.

The next logical step is to compute the error for known perturbations of the system. Can one now go backward and determine the perturbations which give rise to an observed error? At this time, the answer appears to be that this cannot be done. There are about a dozen variables used in the different error analyses, and it is logical that any particular observed harmonic set could be the result of an essentially infinite combination of different error terms. The measurement system used here is quite suited to giving the amplitude and phase of the various harmonic terms, but it cannot explicitly determine their origin. To do this would require additional information not now available. A possible solution would be to modify the patterns so that their different interconnections could be used to obtain additional error data. Such work is, however, beyond the scope of this contract.

Litton's results with the 1.5 and 0.9-inch diameter patterns have indicated that the practical resolution limit of the test equipment, both electrical and mechanical, has been reached.

The residual errors all appear to be about the same magnitude, and sum to the order of 6 to 10 arc minutes under best conditions. The fixture is not capable of much finer alignment and, indeed, already gives trouble in setting up the engineering models for tests. Electronic resolution in the simple oscilloscope methods is limited by signal-to-noise considerations. Any improvement would require a change of method; for example, to a null-balance a-c phase detector system.

This problem exists simply because the resolver performance has been much better than expected, and the original design of the test equipment and fixtures was, of course, accomplished before this performance could be evaluated.

SECTION XI

CONCLUSIONS

11.1 GENERAL

A miniature capacitive resolver has been built which satisfies the design goals of this program. The size is that specified: 0.9 inches in diameter and 0.13 inches in length, while the weight of 4.7 grams is considerably less than the two ounces (56.7 gm) required. The device is illustrated in figure 51 (approximately actual size). The accuracy is also that of the design goal: the worst-case error is 10 arc minutes in a full 360° rotation.

Figure 51. Engineering Model of Miniature Capacitive Resolver (Shown with 8 Auxiliary Leads on Pickoff Electronics and 2 Auxiliary Leads on Pattern)

The working elements have been fabricated by the batch technique that is typical of processing used in the semiconductor industry. The critical operations of capacitive electrode design and generation are performed only once; the resulting artwork is reduced in size and used in photo-etching techniques to generate any desired number of duplicate devices, all possessing the precision of the original design.

A versatile analytical technique which closely combines both experimental measurements and theoretical models has been developed. It is based on

the description of the output of the resolver in terms of sets of Fourier coefficients of the functions of device angular rotation and can be used both to process experimental data and to predict the effect of many possible geometric contributions to device error. Computer programs have been developed to enable these effects to be studied over a wide range of parameter variation, both singly and in combinations.

The current limitation of the performance of this first generation device has been found to be in the test equipment, and not in the device itself. An intrinsic precision of better than 5 arc minutes will be masked by test fixture alignment problems and electrical measuring instrument limitations at 100 Khz. Within these limits, however, a number of options are available. It should be possible to reduce the diameter of the device, perhaps by as much as a third, and still retain accuracy in the 10 arc minute range. An increase in the diameter would allow the addition of more capacitive elements, allowing a full coordinate transformation to be mechanized. The current hybrid microcircuit signal processing electronics could be replaced with a single monolithic chip, with possible improved performance and a greater reliability. It is possible to include more processing in the electronics package; for example, an integral phase detector to obtain angular position directly as a d-c voltage.

The ultimate accuracy of a capacitive resolver has certainly not yet been reached. Some factors limiting the performance of the device would be the effect of fringing fields at the edges of the capacitive elements and the flatness of the capacitive plates. The former effect would be overcome in part by correction of the pattern shapes for fringing effects. The latter problem is a typical one of cost-vs-performance trade-offs in the specifications of materials and processes.

The capacitive resolver is clearly worthy of consideration as an element in future guidance and control systems.

APPENDIX

This appendix contains summaries of test data reduction for elements of the miniature capacitive resolver. These summaries are presented in the order listed in the tabulated results throughout the text of the report (23 pages).

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B128 062768	1.5 STD	1.103E-03	4.366E-04	5	5	12281
1B228 062768	1.5 STD	1.060E-03	4.593E-04	6	5	12282
1B328 062768	1.5 STD	1.357E-03	5.216E-04	5	5	12283
1B428 062768	1.5 STD	1.073E-03	4.545E-04	5	5	12284

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.003195	0.0	-0.012425	0.0	-0.004724	0.0	0.006740	0.0
2	0.477618	0.878568	0.879260	-0.470342	-0.502370	-0.864653	-0.882016	0.471220
3	-0.010262	0.000642	-0.002348	0.004398	0.006704	0.007218	0.004611	-0.012570
4	-0.001782	0.000090	0.001036	-0.001049	0.001561	-0.000355	-0.000859	0.001870
5	-0.000228	-0.000040	0.000157	-0.000078	0.000108	-0.000027	-0.000014	0.000202

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-61.47 DEGREES　　-61.55 DEGREES　　-59.84 DEGREES　　-61.89 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -61.19 DEGREES, DIFFERENCE IN ANGLES = 5.316E-01 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	0.001529	0.0	0.019165	0.0
2	1.999711	-0.018553	-0.018560	1.999904
3	0.003531	0.017851	-0.018056	0.003208
4	0.003309	-0.000651	0.001709	-0.003032
5	0.000155	-0.000299	-0.000181	-0.000274

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 35.11 ARC MINUTES AT 80.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000011	0.0
2	0.000620	0.000843
3	-0.008083	0.000111
4	-0.000000	-0.000022
5	0.000205	-0.001628

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18119 070368	1.5 STD	1.695E-03	7.619E-04	5	5	12191
18219 070368	1.5 STD	2.307E-03	8.937E-04	5	5	12192
18319 070368	1.5 STD	1.873E-03	9.217E-04	5	5	12193
18419 070368	1.5 STD	1.540E-03	6.717E-04	5	5	12194

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	0.003293	0.0	-0.012529	0.0	-0.002007	0.0	0.014747	0.0
2	0.452721	0.891653	0.891184	-0.453645	-0.445839	-0.895114	-0.896255	0.443539
3	-0.014779	-0.000461	-0.004518	0.006946	0.009672	0.010108	0.007272	-0.016936
4	-0.001659	0.000242	0.001335	-0.000489	0.001466	-0.000905	-0.000883	0.001996
5	-0.000140	-0.000132	0.000109	0.000073	0.000151	0.000138	0.000193	0.000016

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-63.08 DEGREES　　-63.02 DEGREES　　-63.52 DEGREES　　-63.67 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -63.32 DEGREES, DIFFERENCE IN ANGLES = 2.194E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	0.005299	0.0	0.027276	0.0
2	1.999984	-0.000763	-0.000768	1.999968
3	0.006115	0.025926	-0.026199	0.004796
4	0.002879	-0.001671	0.001754	-0.002832
5	0.000342	-0.000201	0.000031	0.000097

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 8.83 ARC MINUTES AT 340.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000005	0.0
2	0.000606	0.000086
3	0.000475	0.000001
4	0.000007	-0.000221
5	0.000019	-0.001427

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B136 070868	1.5 STD	6.974E-04	3.320E-04	5	5	12361
1B236 070868	1.5 STD	8.854E-04	2.965E-04	5	5	12362
1B336 070968	1.5 STD	7.436E-04	3.058E-04	5	5	12363
1B436 070968	1.5 STD	1.007E-03	4.483E-04	5	5	12364

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.007304	0.0	-0.012079	0.0	-0.006871	0.0	0.000750	0.0
2	0.459771	0.888037	0.887979	-0.459885	-0.455354	-0.890311	-0.890433	0.455115
3	-0.007779	0.001424	-0.000995	0.001544	0.003579	0.006175	0.004420	-0.009956
4	-0.001310	0.000152	0.000830	-0.001049	0.001179	-0.000313	-0.000529	0.001133
5	0.000156	-0.000141	-0.000061	-0.000132	0.000113	0.000079	0.000311	-0.000130

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-62.63 DEGREES	-62.62 DEGREES	-62.91 DEGREES	-62.93 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -62.77 DEGREES, DIFFERENCE IN ANGLES = 1.994E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.000433	0.0	0.012830	0.0
2	1.999991	-0.000068	-0.000072	1.999991
3	0.002737	0.012004	-0.012505	0.002279
4	0.002395	-0.000820	0.001030	-0.002356
5	0.000194	0.000112	-0.000123	0.000351

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 9.06 ARC MINUTES AT 290.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000011	0.0
2	0.000288	0.001474
3	0.000436	0.000007
4	-0.000177	0.000021
5	0.000052	-0.001186

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B136 071668 QT	1.5 STD	1.056E-03	4.131E-04	6	5	12361
1B236 071668 QT	1.5 STD	9.797E-04	3.947E-04	5	5	12362
1B336 071668 QT	1.5 STD	1.061E-03	3.690E-04	6	5	12363
1B436 071668 Q	1.5 STD	8.074E-04	3.217E-04	5	5	12364

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.009145	0.0	-0.013239	0.0	-0.008230	0.0	-0.001842	0.0
2	0.483263	0.875475	0.889313	-0.457300	-0.431117	-0.902296	-0.889435	0.457063
3	-0.006926	0.002974	0.000440	0.000337	0.001428	0.005464	0.003458	-0.007779
4	-0.000630	0.000039	0.000785	-0.000228	0.001261	0.000096	-0.000196	0.000330
5	-0.000055	-0.000512	0.000136	0.000117	0.000190	-0.000179	0.000025	-0.000139

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-61.10 DEGREES -62.79 DEGREES -64.46 DEGREES -62.80 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -62.79 DEGREES, DIFFERENCE IN ANGLES = 6.612E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.000915	0.0	0.011397	0.0
2	1.999140	-0.000229	-0.000233	1.999998
3	0.002835	0.008243	-0.008357	0.002267
4	0.001879	-0.000218	0.000888	-0.000695
5	0.000394	-0.000124	0.000277	-0.000023

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 10.74 ARC MINUTES AT 65.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000011	0.0
2	0.001547	0.001735
3	0.000169	0.000503
4	0.000076	-0.000048
5	0.000167	-0.000643

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18140 071768	PQT 1.5 STD	8.670E-04	3.145E-04	5	5	12401
18240 071768	PQT 1.5 STD	7.378E-04	2.933E-04	5	5	12402
18340 071768	PQT 1.5 STD	8.442E-04	3.000E-04	5	5	12403
18440 071768	PQT 1.5 STD	1.024E-03	3.430E-04	5	5	12404

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.046321	0.0	-0.054680	0.0	-0.045028	0.0	-0.034484	0.0
2	0.486283	0.873801	0.885580	-0.464487	-0.437068	-0.899429	-0.888359	0.459150
3	-0.022984	-0.030648	0.014928	0.041145	-0.005838	-0.032131	0.013582	0.023147
4	0.000255	0.000194	-0.000441	0.000109	0.000880	-0.000798	-0.000435	0.000361
5	0.000156	0.000150	0.000378	0.000266	0.000026	-0.000098	-0.000146	-0.000070

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-60.90 DEGREES	-62.32 DEGREES	-64.08 DEGREES	-62.67 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -62.49 DEGREES, DIFFERENCE IN ANGLES = 1.038E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.001293	0.0	0.020196	0.0
2	1.999228	-0.000036	-0.000038	1.999990
3	0.011047	0.013197	-0.013973	0.011423
4	0.000490	-0.001065	-0.000039	-0.000249
5	-0.000277	0.000037	0.000494	-0.000377

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 25.82 ARC MINUTES AT 60.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000063	0.0
2	0.003305	0.006268
3	0.000285	0.000207
4	-0.000077	-0.000072
5	-0.000277	-0.000181

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18142 072468	0.9 STD	9.634E-04	3.473E-04	6	5	12421
18242 072468	0.9 STD	9.847E-04	2.852E-04	6	5	12422
18342 072468	0.9 STD	5.519E-04	2.391E-04	5	5	12423
18442 072468	0.9 STD	7.855E-04	2.413E-04	5	5	12424

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.012027	0.0	-0.009297	0.0	-0.013168	0.0	-0.010456	0.0
2	0.981209	0.192949	0.192610	-0.981275	-0.978911	-0.204288	-0.202466	0.979289
3	-0.000717	-0.002740	-0.009328	0.001096	0.008038	0.006278	0.000725	-0.005735
4	-0.000453	-0.000603	-0.000107	0.000956	-0.000573	-0.000274	0.001707	-0.000073
5	-0.000156	-0,000492	-0,000322	-0,000239	0,000090	-0,000182	0,000286	0,000491

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-11.12 DEGREES	-11.11 DEGREES	-11.79 DEGREES	-11.68 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.42 DEGREES, DIFFERENCE IN ANGLES = 3.160E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	0.001141	0.0	-0.001159	0.0
2	1.999965	0.001103	0.001103	1.999973
3	-0.011569	-0.004911	0.006612	-0.010199
4	-0.000087	-0.000340	0.000920	-0.001872
5	-0.000394	-0.000040	0.000949	0.000074

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 24.57 ARC MINUTES AT 100.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000005	0.0
2	0.002304	-0.006013
3	0.000885	-0.000498
4	0.000675	0.000259
5	0.000148	-0.000446

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18127 072668	0.9 STD	7.731E-04	2.427E-04	6	5	12271
18227 072668	0.9 STD	7.705E-04	2.656E-04	5	5	12272
18327 072668	0.9 STD	6.738E-04	2.346E-04	6	5	12273
18427 072668	0.9 STD	8.775E-04	3.102E-04	5	5	12274

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.012802	0.0	0.000478	0.0	0.000021	0.0	-0.008750	0.0
2	0.980226	0.197881	0.199399	-0.979919	-0.980044	-0.198781	-0.193128	0.981174
3	-0.001813	-0.002858	-0.011934	0.001803	0.010520	0.009474	0.001792	-0.009679
4	-0.000086	0.000693	-0.000526	0.001076	-0.000144	-0.000493	0.000505	-0.001447
5	-0.000315	0.000342	0.000282	0.000116	0.000351	-0.000166	-0.000158	-0.000057

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-11.41 DEGREES -11.50 DEGREES -11.47 DEGREES -11.14 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.38 DEGREES, DIFFERENCE IN ANGLES = 6.040E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.012823	0.0	-0.009228	0.0
2	1.999998	0.002108	0.002108	1.999988
3	-0.016144	-0.006001	0.008216	-0.015897
4	0.000714	0.000949	-0.000563	-0.002666
5	-0.000105	0.000831	-0.000432	0.000193

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 8.94 ARC MINUTES AT 40.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000014	0.0
2	-0.000906	-0.001604
3	0.000678	-0.000506
4	0.000092	0.000076
5	0.000097	-0.000843

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B122 073068	0.9 STD	9.994E-04	3.502E-04	6	5	12221
1B222 073068	0.9 STD	7.440E-04	2.753E-04	5	5	12222
1B322 073068	0.9 STD	7.760E-04	3.015E-04	6	5	12223
1B422 073068	0.9 STD	5.876E-04	2.655E-04	5	5	12224

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.013800	0.0	0.003009	0.0	0.005952	0.0	-0.006684	0.0
2	0.977311	0.211810	0.217935	-0.975964	-0.976589	-0.215117	-0.205085	0.978744
3	-0.002530	-0.004014	-0.014398	0.001787	0.011225	0.011796	0.003198	-0.011601
4	0.000007	0.000455	-0.000606	0.001249	0.000667	-0.000370	0.000314	-0.001156
5	-0.000499	0.000334	0.000214	0.000283	0.000474	-0.000119	-0.000127	-0.000023

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-12.23 DEGREES   -12.59 DEGREES   -12.42 DEGREES   -11.83 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -12.27 DEGREES, DIFFERENCE IN ANGLES = 5.715E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.019752	0.0	-0.009693	0.0
2	1.999996	0.001995	0.001995	1.999954
3	-0.019078	-0.008669	0.010447	-0.019486
4	-0.000034	0.001056	-0.000704	-0.002476
5	-0.000296	0.001032	-0.000456	0.000057

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 5.33 ARC MINUTES AT 155.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000000	0.0
2	-0.000064	0.000226
3	0.000556	-0.000638
4	0.000079	-0.000171
5	0.000091	-0.000612

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B116 080168	0.9 STD	1.101E-03	4.405E-04	5	5	12161
1B216 080168	0.9 STD	1.046E-03	4.490E-04	5	5	12162
1B316 080168	0.9 STD	1.376E-03	5.130E-04	6	5	12163
1B416 080168	0.9 STD	9.430E-04	3.765E-04	5	5	12164

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.013193	0.0	0.011177	0.0	0.016786	0.0	-0.002626	0.0
2	0.971801	0.235803	0.244164	-0.969734	-0.970288	-0.241953	-0.228870	0.973457
3	-0.006824	-0.005799	-0.019582	0.002087	0.014311	0.018615	0.007394	-0.017782
4	-0.000197	0.000847	-0.001808	0.002426	0.000573	-0.001055	0.000808	-0.001806
5	-0.000502	0.000047	0.000247	0.000517	0.000207	-0.000538	0.000008	-0.000579

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-13.64 DEGREES	-14.13 DEGREES	-14.00 DEGREES	-13.23 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -13.75 DEGREES, DIFFERENCE IN ANGLES = 6.946E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.029979	0.0	-0.013803	0.0
2	1.999987	0.002425	0.002424	1.999935
3	-0.030020	-0.011895	0.014753	-0.030081
4	0.000676	0.001937	-0.000824	-0.004907
5	0.000073	0.000917	-0.001035	-0.000433

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 9.29 ARC MINUTES AT 340.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000004	0.0
2	-0.000237	-0.000055
3	0.000522	-0.001078
4	0.000237	-0.000140
5	0.000281	-0.001399

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18133 080568	0.9 STD	7.722E-04	3.039E-04	6	5	12331
18233 080568	0.9 STD	7.048E-04	2.826E-04	5	5	12332
18333 080568	0.9 STD	7.965E-04	2.844E-04	5	5	12333
18433 080568	0.9 STD	7.091E-04	2.647E-04	7	5	12334

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.014478	0.0	-0.003646	0.0	-0.004416	0.0	-0.010313	0.0
2	0.979033	0.203703	0.204315	-0.978906	-0.979199	-0.202907	-0.197328	0.980338
3	-0.000639	-0.002161	-0.010252	0.001155	0.008974	0.008031	0.000350	-0.007785
4	0.000134	0.000674	-0.000808	0.001088	0.000281	-0.000470	0.000215	-0.000858
5	-0.000021	0.000199	0.000377	0.000006	0.000038	-0.000430	-0.000505	0.000025

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-11.75 DEGREES   -11.79 DEGREES   -11.71 DEGREES   -11.38 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.66 DEGREES, DIFFERENCE IN ANGLES = 7.260E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.010062	0.0	-0.006667	0.0
2	1.999999	0.002534	0.002534	1.999986
3	-0.012862	-0.005555	0.006198	-0.012406
4	0.000535	0.001021	-0.000277	-0.002181
5	0.000417	0.000475	-0.000591	0.000654

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 8.83 ARC MINUTES AT 100.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000007	0.0
2	-0.000591	-0.001290
3	0.000945	-0.000421
4	-0.000101	0.000378
5	0.000184	-0.000677

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANGLE	ERROR	ITER	N	CODE
1B131 080768 Q1	0.9 SIN	2.371E-04	2.550E-06	5	5	12311
1B231 080768 Q1	0.[illegible] SIN	8.312E-06	2.860E-06	6	5	12312
1B331 080768 Q[illegible]	[illegible] SIN	5.404E-04	2.[illegible]E-06	5	5	12313
1B431 080768 Q[illegible]	0.9 SIN	6.763E-06	1.9[illegible]7E-06	[illegible]	[illegible]	12314

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DEFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.014006	0.0	-0.000355	0.0	-0.006269	0.0	-0.011293	0.0
2	0.987125	0.159955	0.202700	-0.979261	-0.960919	-0.265846	-0.199859	0.979825
3	0.000275	-0.002707	-0.016020	0.000796	0.007037	0.010110	0.001228	-0.006521
4	0.000354	0.000666	-0.000597	0.000916	0.000[illegible]61	-0.000039	0.000566	-0.000849
5	-0.000250	0.000636	-0.000080	0.000292	0.000217	0.000191	0.000094	-0.000269

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-9.20 DEGREES -11.70 DEGREES -16.11 DEGREES -11.55 DEGREES

---OPPOSITE PLATE SEPARATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -1[illegible].[illegible] DEGREES, DIFFERENCE IN ANGLES = 2.563E-02 DEGREES, ITER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.009735	0.0	-0.011057	0.0
2	1.998105	0.000817	0.000818	1.999997
3	-0.011829	-0.000805	0.011262	-0.012581
4	0.000522	0.001520	-0.000268	-0.002057
5	-0.000021	0.000666	-0.000239	-0.000509

ERROR RESULT---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 6.[illegible]9 ARC MINUTES AT 55.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000010	0.0
2	-0.000490	-0.001239
3	0.000222	0.000029
4	0.000359	-0.000323
5	0.000071	-0.000003

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18133 080968	PQT 0.9 STD	5.254E-04	2.000E-40	5	5	12331
18233 080968	PQT 0.9 STD	8.019E-04	2.719E-04	6	5	12332
18333 080968	PQT 0.9 STD	6.222E-04	2.717E-04	5	5	12333
18433 080968	PQT 0.9 STD	8.466E-04	2.488E-04	5	5	12334

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	0.002075	0.0	0.012673	0.0	0.008157	0.0	0.001948	0.0
2	0.987920	0.154969	0.198006	-0.980201	-0.969004	-0.247048	-0.202779	0.979225
3	0.005782	0.011616	-0.018532	-0.021080	0.006526	0.026310	-0.001019	-0.018855
4	0.000228	-0.000132	-0.001713	0.001724	0.001124	-0.000931	0.001331	-0.000623
5	-0.000190	-0.000156	0.000051	0.000054	0.000065	-0.000224	0.000070	0.000462

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-8.91 DEGREES	-11.42 DEGREES	-14.30 DEGREES	-11.70 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.58 DEGREES, DIFFERENCE IN ANGLES = 2.450E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.006081	0.0	-0.010725	0.0
2	1.997789	0.000854	0.000855	1.999993
3	-0.006465	-0.013216	0.016976	-0.004845
4	-0.000280	0.001167	0.001163	-0.003663
5	-0.000127	0.000232	0.000308	0.000268

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 15.17 ARC MINUTES AT 355.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000008	0.0
2	0.002188	0.000210
3	0.000438	-0.000427
4	0.000961	0.000435
5	0.000585	-0.000840

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B131 081568	QS6 0.9 STD	8.784E-04	3.300E-04	6	5	12311
1B231 081568	QS6 0.9STD	6.830E-04	3.308E-04	5	5	12312
1B331 081568	QS6 0.9 STD	8.887E-04	3.255E-04	5	5	12313
1B431 081568	QS6 0.9 STD	7.282E-04	2.487E-04	5	5	12314

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.015431	0.0	0.011085	0.0	-0.004718	0.0	-0.010214	0.0
2	0.976091	0.217363	0.205951	-0.978562	-0.981387	-0.192069	-0.201503	0.979488
3	-0.004164	-0.001707	-0.001164	0.005151	0.006594	0.005479	0.004239	-0.006741
4	-0.001101	0.001073	0.001726	-0.002565	-0.000349	0.001167	-0.000560	0.000536
5	-0.000208	0.001099	-0.000311	0.000022	0.001227	-0.000123	-0.000331	-0.000324

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-12.55 DEGREES	-11.89 DEGREES	-11.07 DEGREES	-11.62 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.78 DEGREES, DIFFERENCE IN ANGLES = 2.944E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.010713	0.0	-0.021299	0.0
2	1.999833	0.001028	0.001028	1.999994
3	-0.012733	-0.002280	0.000197	-0.013060
4	-0.000668	0.000358	-0.000075	0.003856
5	-0.000081	0.001884	-0.000268	-0.000221

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 42.51 ARC MINUTES AT 195.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000067	0.0
2	-0.010019	-0.001087
3	0.000345	0.000779
4	-0.001058	-0.000139
5	0.000068	0.001124

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18131 081668QS10	0.9 STD	1.516E-03	5.352E-04	5	5	12311
18231 081668QS10	0.9 STD	1.222E-03	4.885E-04	6	5	12312
18331 081668QS10	0.9 STD	1.587E-03	5.935E-04	5	5	12313
18431 081668QS10	0.9 STD	6.743E-04	2.339E-04	5	5	12314

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.006647	0.0	0.043736	0.0	0.005721	0.0	0.005155	0.0
2	0.969818	0.243834	0.209573	-0.977794	-0.986139	-0.165922	-0.201002	0.979591
3	-0.007578	-0.000702	0.020932	0.013225	0.005347	-0.000103	0.011603	-0.003946
4	-0.001415	0.003445	0.005020	-0.008233	-0.002836	0.003985	-0.001467	0.002403
5	0.000099	0.003528	0.000613	0.000580	0.003734	-0.000591	-0.000511	-0.000763

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-14.11 DEGREES   -12.10 DEGREES   -9.55 DEGREES   -11.60 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.84 DEGREES, DIFFERENCE IN ANGLES = 7.279E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.012368	0.0	-0.038580	0.0
2	1.998415	-0.000254	-0.000254	1.999980
3	-0.012077	0.004643	-0.015440	-0.011979
4	0.000842	-0.001265	0.000899	0.012426
5	0.000568	0.005465	-0.001749	-0.000083

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION =105.46 ARC MINUTES AT 345.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000147	0.0
2	-0.024252	0.000182
3	0.000242	0.003551
4	-0.004509	0.000178
5	-0.000115	0.002853

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	K	CODE
1B133 082168	PS6 0.9 STD	6.131E-04	2.276E-04	5	5	12331
1B233 082168	PS6 0.9 STD	5.801E-04	2.266E-04	5	5	12332
1B333 082168	PS6 0.9 STD	6.389E-04	2.306E-04	5	5	12333
1B433 082168	PS6 0.9 STD	8.127E-04	2.285E-04	6	5	12334

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.007582	0.0	0.001425	0.0	0.003432	0.0	-0.001229	0.0
2	0.982055	0.188597	0.195808	-0.980643	-0.980810	-0.194971	-0.183985	0.982930
3	-0.006649	-0.019161	-0.004441	0.019022	0.003304	-0.009546	0.007388	0.009381
4	0.000113	0.000260	-0.000229	0.000515	0.001061	0.000331	-0.000639	-0.000883
5	-0.000301	0.000128	0.000477	0.000330	0.000308	-0.000081	-0.000189	-0.000398

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-10.87 DEGREES	-11.29 DEGREES	-11.24 DEGREES	-10.60 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -11.00 DEGREES, DIFFERENCE IN ANGLES = 5.502E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.011014	0.0	-0.002654	0.0
2	1.999988	0.001921	0.001920	1.999964
3	-0.012830	-0.005186	0.007355	-0.013371
4	-0.000833	0.000457	-0.001106	-0.000949
5	-0.000293	0.000574	-0.000985	-0.000061

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 10.94 ARC MINUTES AT 330.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000008	0.0
2	0.001812	-0.001048
3	0.000583	-0.000456
4	0.000156	-0.000226
5	-0.000162	-0.000030

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B133 082268PS10	0.9 STD	8.166E-04	2.190E-04	5	5	12331
1B233 082268PS10	0.9 STD	7.876E-04	2.313E-04	5	5	12332
1B333 082268PS10	0.9 STD	5.436E-04	2.231E-04	5	5	12333
1B433 082268PS10	0.9 STD	5.689E-04	2.092E-04	5	5	12334

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM OFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	0.019359	0.0	0.028506	0.0	0.030150	0.0	0.025371	0.0
2	0.987305	0.158841	0.166058	-0.986116	-0.986159	-0.165806	-0.155042	0.987909
3	-0.018627	-0.043614	0.006728	0.043881	-0.007322	-0.03[illegible]122	0.017949	0.032501
4	-0.000826	-0.000267	0.000154	-0.000381	0.001027	0.000705	-0.000972	-0.000215
5	-0.000085	-0.000084	0.000114	0.000120	0.000344	-0.000005	-0.000073	-0.000152

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-9.14 DEGREES	-9.56 DEGREES	-9.54 DEGREES	-8.92 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -9.29 DEGREES, DIFFERENCE IN ANGLES = 5.144E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.010792	0.0	-0.003135	0.0
2	1.999987	0.001796	0.001795	1.999968
3	-0.014059	-0.006342	0.007010	-0.014362
4	-0.002092	0.000007	-0.000918	0.000673
5	-0.000390	0.000196	-0.000313	-0.000104

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 11.32 ARC MINUTES AT 310.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000006	0.0
2	0.001775	-0.001714
3	0.000682	-0.000367
4	0.000045	-0.000195
5	-0.000227	0.000691

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B133 082868	PTX 0.9 STD	6.820E-04	2.505E-04	5	5	12331
1B233 082868	PTX 0.9 STD	4.159E-04	1.568E-04	5	5	12332
1B333 082868	PTX 0.9 STD	7.012E-04	2.312E-04	5	5	12333
2B433 082968	PTX 0.9 STD	5.964E-04	1.802E-04	5	5	22334

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	0.043304	0.0	0.052632	0.0	0.049628	0.0	0.045237	0.0
2	0.983847	0.179011	0.190170	-0.981752	-0.982921	-0.184031	-0.169972	0.985450
3	0.013520	0.065644	-0.018698	-0.065258	0.018816	0.068709	-0.015389	-0.070565
4	-0.002969	0.002293	-0.002977	-0.002264	0.004022	-0.002235	0.002706	0.002574
5	0.000060	0.000341	-0.000243	-0.000143	0.000438	-0.000679	-0.000003	-0.000049

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
-10.31 DEGREES	-10.96 DEGREES	-10.60 DEGREES	-9.79 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -10.42 DEGREES, DIFFERENCE IN ANGLES = 4.199E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.006324	0.0	-0.007395	0.0
2	1.999991	0.001466	0.001465	1.999894
3	-0.006039	-0.000981	0.001205	-0.006137
4	-0.003627	0.007498	0.007369	0.001188
5	0.000396	0.001013	0.000242	-0.000089

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 25.62 ARC MINUTES AT 185.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000010	0.0
2	-0.003152	0.000117
3	0.000692	-0.000638
4	-0.000122	0.000055
5	0.003717	0.001204

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B128 083068	PTY 0.9 STD	6.275E-04	2.562E-04	5	5	12281
1B228 083068	PTY 0.9 STD	4.681E-04	2,048E-04	5	5	12282
1B328 083068	PTY 0.9 STD	8.770E-04	2.533E-04	5	5	12283
1B428 083068	PTY 0.9 STD	5.756E-04	2.037E-04	5	5	12284

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	0.076799	0.0	0.087778	0.0	0.084283	0.0	0.080607	0.0
2	0.984892	0.173169	0.183263	-0.983064	-0.984184	-0.177153	-0.163539	0.986537
3	0.069587	-0.024409	-0.079749	0.017944	0.074052	-0,010484	-0.067035	0.015405
4	0.002189	-0.002520	0.001835	0.004699	-0.003595	0.001624	-0.001922	-0.003242
5	-0.000538	0.000316	0.000072	0.000168	0.000129	0.000021	0.000006	0.000042

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

-9.97 DEGREES　　-10.56 DEGREES　　-10,20 DEGREES　　-9,41 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = -10.04 DEGREES, DIFFERENCE IN ANGLES = 5.096E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.007484	0.0	-0.007170	0.0
2	1.999994	0.001779	0.001779	1.999899
3	-0,008974	-0,011547	0,011071	-0,006749
4	0.002924	-0.006487	-0,007234	-0.004984
5	-0.000320	0.000655	-0.000132	-0.000054

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 20.47 ARC MINUTES AT 325.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000006	0.0
2	0.002070	-0.000195
3	0.000712	-0.000528
4	-0.000335	0.000475
5	-0.003432	-0.001977

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
1B129 091768	0.9 HO	6.508E-04	2.700E-04	5	5	12291
1B229 091768	0.9 HO	9.088E-04	2.766E-04	5	5	12292
1B329 091768	0.9 HO	8.390E-04	2.657E-04	5	5	12293
1B429 091768	0.9 HO	1.018E-03	3.604E-04	5	5	12294

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.011472	0.0	0.008491	0.0	0.003476	0.0	-0.002893	0.0
2	0.985456	-0.169933	-0.171685	-0.985153	-0.985131	0.171809	0.171001	0.985271
3	-0.001254	0.000003	0.004890	0.009780	0.014140	0.004331	0.008848	-0.005420
4	-0.000669	0.000740	0.000302	0.000104	0.000965	-0.000819	0.000241	-0.000147
5	0.000151	0.000078	0.000196	0.000043	0.000022	-0.000616	-0.000528	-0.000081

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

9.78 DEGREES	9.89 DEGREES	9.89 DEGREES	9.85 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = 9.85 DEGREES, DIFFERENCE IN ANGLES = 1.371E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.014948	0.0	-0.011384	0.0
2	2.000000	0.000478	0.000479	2.000000
3	-0.013033	-0.009265	0.008851	-0.012975
4	-0.002191	0.000550	0.000071	-0.000249
5	-0.000341	0.000618	-0.000480	-0.000556

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 6.58 ARC MINUTES AT 115.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000004	0.0
2	-0.001160	0.000968
3	0.000102	-0.000608
4	-0.000371	-0.000210
5	0.000154	0.000482

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18118 092468 HO	0.9 STD	1.404E-03	4.956E-04	5	5	12181
18218 092468 HO	0.9 STD	1.705E-03	5.712E-04	5	5	12182
18318 092468 HO	0.9 STD	1.229E-03	4.422E-04	6	5	12183
18418 092468 HO	0.9 STD	1.079E-03	4.685E-04	5	5	12184

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.011965	0.0	0.006563	0.0	0.012176	0.0	-0.010031	0.0
2	0.982936	-0.183950	-0.182499	-0.983206	-0.985425	0.170112	0.174636	0.984633
3	-0.005701	0.001304	0.005122	0.017507	0.021550	0.008552	0.014202	-0.008572
4	-0.000715	0.000920	0.000313	0.000320	0.000957	-0.001861	-0.000130	-0.001141
5	0.000283	0.000413	-0.000131	0.000373	0.000141	-0.001033	-0.000462	0.000331

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

PLATE 1	PLATE 2	PLATE 3	PLATE 4
10.60 DEGREES	10.52 DEGREES	9.79 DEGREES	10.06 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = 10.24 DEGREES, DIFFERENCE IN ANGLES = 4.464E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.024142	0.0	-0.016594	0.0
2	1.999949	0.001558	0.001559	1.999983
3	-0.022993	-0.016326	0.017631	-0.021253
4	-0.002858	0.001537	0.000366	-0.001481
5	-0.000840	0.001185	-0.000223	-0.000249

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 9.04 ARC MINUTES AT 240.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000011	0.0
2	0.000189	0.000994
3	0.000482	-0.001061
4	-0.000002	0.000155
5	0.000479	0.000346

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18118 092768 ES	0.9 HO	2.173E-03	9.402E-04	6	5	12181
18218 092768 ES	0.9 HO	2.000E-03	9.460E-04	5	5	12182
18318 092768 ES	0.9 HO	2.173E-03	9.402E-04	6	5	12183
18418 092768 ES	0.9 HO	2.000E-03	9.460E-04	5	5	12184

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.011941	0.0	0.008110	0.0	0.011941	0.0	-0.008110	0.0
2	0.938421	-0.345496	-0.346241	-0.938147	-0.938421	0.345496	0.346241	0.938147
3	-0.013887	0.001619	0.000100	0.013558	0.013887	-0.001619	-0.000100	-0.013558
4	0.000088	0.001120	0.001143	0.001008	-0.000088	-0.001120	-0.001143	-0.001008
5	0.000216	0.000440	0.000271	-0.000022	-0.000216	-0.000440	-0.000271	0.000022

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

20.21 DEGREES	20.26 DEGREES	20.21 DEGREES	20.26 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = 20.23 DEGREES, DIFFERENCE IN ANGLES = 2.273E-02 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.023882	0.0	-0.016221	0.0
2	1.999999	0.000793	0.000794	2.000001
3	-0.023230	-0.015563	0.017447	-0.020758
4	-0.001866	0.001250	0.000639	-0.002981
5	-0.000801	0.000564	-0.000128	-0.000528

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 7.96 ARC MINUTES AT 220.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000009	0.0
2	0.000136	0.000929
3	0.000244	-0.001199
4	0.000314	0.000268
5	0.000476	-0.000273

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
18130 101068 ES	0.9 HO	1.086E-03	3.955E-04	5	5	12301
18230 101068 ES	0.9 HO	1.252E-03	4.333E-04	5	5	12302
18130 101068 ES	0.9 HO	1.086E-03	3.955E-04	5	5	12301
18230 101068 ES	0.9 HO	1.252E-03	4.333E-04	5	5	12302

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.006375	0.0	0.003911	0.0	0.006375	0.0	-0.003911	0.0
2	0.930426	-0.366480	-0.366297	-0.930498	-0.930426	0.366480	0.366297	0.930498
3	-0.007760	0.000687	0.000397	0.007568	0.007760	-0.000687	-0.000397	-0.007568
4	-0.000423	0.000503	0.000782	0.000546	0.000423	-0.000503	-0.000782	-0.000546
5	-0.000134	0.000211	0.000141	0.000148	0.000134	-0.000211	-0.000141	-0.000148

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

21.50 DEGREES	21.49 DEGREES	21.50 DEGREES	21.49 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = 21.49 DEGREES, DIFFERENCE IN ANGLES = 5.659E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.012750	0.0	-0.007821	0.0
2	1.999999	-0.000198	-0.000197	1.999999
3	-0.012289	-0.009577	0.009739	-0.011613
4	-0.001272	-0.000331	0.000311	-0.001882
5	-0.000440	-0.000238	0.000270	-0.000302

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 6.00 ARC MINUTES AT 210.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	0.000007	0.0
2	0.000916	0.000395
3	0.000067	-0.000783
4	0.000173	-0.000022
5	-0.000003	-0.000151

---CAPACITIVE RESOLVER DATA REDUCTION---

RUN NUMBER	TYPE	ANORM	ENORM	IER	M	CODE
12123 013069 ES	0.9 HO	9.947E-04	4.079E-04	8	5	12231
12223 013069 ES	0.9 HO	9.900E-04	3.705E-04	6	5	12232
12123 013069 ES	0.9 HO	9.947E-04	4.079E-04	8	5	12231
12223 013069 ES	0.9 HO	9.900E-04	3.705E-04	6	5	12232

FOURIER COEFFICIENTS FROM COMPUTER PROGRAM DFFOUR---NORMALIZED

	PLATE 1		PLATE 2		PLATE 3		PLATE 4	
K	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)	A(K)	B(K)
1	-0.008143	0.0	0.007274	0.0	0.008143	0.0	-0.007274	0.0
2	0.857614	-0.514294	-0.514376	-0.857565	-0.857614	0.514294	0.514376	0.857565
3	-0.008825	0.003705	0.003257	0.009362	0.008825	-0.003705	-0.003257	-0.009362
4	0.000177	0.000402	0.001263	0.000299	-0.000177	-0.000402	-0.001263	-0.000299
5	-0.000083	0.000242	0.000214	-0.000305	0.000083	-0.000242	-0.000214	0.000305

ANGULAR BIAS BETWEEN PATTERN ZERO AND TURNTABLE ZERO

30.95 DEGREES	30.96 DEGREES	30.95 DEGREES	30.96 DEGREES

---OPPOSITE PLATE SUMMATION WITHOUT TILT CORRECTION---

MEAN BIAS ANGLE = 30.95 DEGREES, DIFFERENCE IN ANGLES = 2.708E-03 DEGREES, JER = 5

FOURIER COEFFICIENTS ROTATED BY BIAS ANGLE

	COSINE PLATES		SINE PLATES	
K	A13(K)	B13(K)	A24(K)	B24(K)
1	-0.016286	0.0	-0.014548	0.0
2	1.999999	0.000094	0.000095	1.999998
3	-0.014848	-0.012081	0.013450	-0.014565
4	-0.000821	0.000314	0.000724	-0.002493
5	-0.000310	-0.000408	-0.000269	-0.000695

ERROR RESIDUE---ERROR FUNCTION RELATIVE TO PATTERN ZERO
MAXIMUM OF ERROR FUNCTION = 6.36 ARC MINUTES AT 130.00 DEGREES

ERROR FUNCTION COEFFICIENTS

K	AER(K)	BER(K) (IN RADIANS)
1	-0.000002	0.0
2	-0.000896	0.000782
3	0.000139	-0.000833
4	0.000382	-0.000190
5	0.000262	-0.000416

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13. ABSTRACT A miniature, pancake-style resolver has been developed which employs the principle of measuring the capacitance between a plane parallel electrode structure. One-half contains a pattern structure electrically excited by a 100 KHz voltage; the other consists of a pickup structure whose output signals are sine and cosine functions of the angular displacement of the two elements. This entire assembly, and its signal processing electronics, is 0.9 inch in diameter and 0.13 inches thick. Its accuracy is at least arc-minutes. Theoretical discussion includes pattern and pickup element design. Experimental discussion includes the computer-generation of patterns and pickup geometries, the fabrication of the elements using the thin-film techniques of the semiconductor industry, and construction of an electronics package using hybrid microcircuits. A special mechanical test fixture was developed which allowed the deliberate introduction of positional errors to evaluate their effects on accuracy. Preliminary work on a 1.5 inch diameter model is also given.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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